A Concept Paper
For
SEPARATION SAFETY MODELING

An FAA/EUROCONTROL Cooperative Effort on
Air Traffic Modeling for Separation Standards

20 May 1998

[This page intentionally blank]

TABLE OF CONTENTS

PREFACE

This report addresses a number of areas related to modeling the effects on aviation safety resulting from a reduction in aircraft separation minima (standards) in airspace where radar separation is provided. The report is largely the work of volunteers, European and American. The form of this report is somewhere between a volume of proceedings of a technical conference on separation and a tightly edited, cohesive volume.   As a consequence, the reader may find technical terms that are used somewhat differently in various report sections as well as a variety of writing styles. The opinions expressed in this report are those of the individual authors and not those of the Federal Aviation Administration, Eurocontrol, other aviation authorities, or the aviation industry.

The report does not address the economic issues associated with reduced separation minima. There are some within the aviation industry and aviation authorities who predict that large economic benefits will accrue with reductions in separation minima in controlled airspace, but most individuals consider these benefits yet to be proven.

ACKNOWLEDGMENTS

    Roger A. Shepherd

Boeing Corporation
    Bob Schwab
    Arek Shakarian
    John Brown

TRW/SETA
    Don Weitzman, TRW/SETA

Material was also adapted from works of the following authors:

    Mark J. Rockman, MITRE/CAASD (adapted by Steve Cohen, FAA)
    Nigel Sylvester-Thorne, Eurocontrol (adapted by Nadine Pilon,
        Eurocontrol)
    Applied Techno-Management Systems (adapted by Steve Cohen, FAA)

The following individuals participated in a number of meetings. Discussions in these meetings materially affected the contents of this report.

    FAA, Washington Headquarters
        Ken Geisinger
        Stephen Cohen
        Diana Liang
        Arthur Salomon
        Tom Kossiaras
        Jack Wojciech

    FAA, Mike Monroney Aeronautical Center
        David N. Lankford
        Alan B. Jones
        James H. Yates
        Shahar Ladecky

    FAA, Williams J. Hughes Technical Center
        Brian Colamosca,
        Bennett Flax,
        Dale Livingston, and
        Robert Rigolizzo

    NASA Langley Research Center
        George C. Greene

    Eurocontrol
        Steve Hockaday
        Mike Perry
        Liz Davies

    National Aerospace Laboratory NLR

[This page intentionally blank]

1.0   INTRODUCTION AND SCOPE

1.1   INTRODUCTION

In today's air traffic environment there is an emphasis on economic, cost-efficient operations and the need to not just maintain aviation safety, but dramatically improve it. With this emphasis has come the requirement to modernize en route and terminal air traffic operations. This is being accomplished by transitioning to satellite-based navigation and surveillance, the equipage of ground facilities and aircraft cockpits with new technology, and the introduction of new airspace procedures and rules.

Both the FAA and EUROCONTROL face this challenge of airspace modernization. An overriding concern of both organizations is that as the modernization occurs, aviation safety is maintained and improved. Most current en route and terminal area separation standards (separation minima) have been in place for decades. Until recently, there were few efforts to change these standards, perhaps because it was felt that the current standards were adequate and a rigorous analysis of the impact of changing the standards would be a major undertaking. The current standards are based on radar separation. There is very little official documentation on the historical development of these standards, but it appears that they were set in large part by a consideration of the ability to maintain separate images of aircraft on radar screens, with additional separation added as a safety margin. Certainly, there is no official indication that mathematical/probabilistic models were developed to aid in the setting of separation standards that would be maintained by radar surveillance. On the other, hand mathematical/probabilistic models have been used for quite some time in the setting of separation standards in oceanic airspace. Most recently they have played a part in the decision to reduce vertical separation standards from 2,000 ft. to 1,000 ft. in portions of the airspace over the North Atlantic. This paper describes the beginnings of an attempt to create a model for use in airspace where radar separation is provided, one that will enable the estimation of the risk of a midair collision or other safety problem (e.g., serious wake vortex encounter) as a function of parameters such as separation minima, accuracy of position information, integrity of systems, and controller automation aids.

1.2   SCOPE OF JOINT ACTIVITIES

The present effort is the result of an action plan for an FAA/EUROCONTROL cooperative effort on air traffic modeling for separation standards. This plan was signed by Mr. Norman Fujisaki, Director of Investment Analysis and Operations Research, Federal Aviation Administration and Mr. Alex Hendriks, Head of the Airspace and Navigation Division, EUROCONTROL. This is one of a number of cooperative action plans sponsored by the FAA/EUROCONTROL Research and Development Committee.

Two teams (North American and European) were formed to carry out the objectives of the action plan. Both teams consisted of volunteers interested in the subject. The scope of the teams' activities were defined by the action plan presented below.

ACTION PLAN FOR FAA/EUROCONTROL COOPERATIVE EFFORT
ON
AIR TRAFFIC MODELING FOR SEPARATION STANDARDS

I.   TASK OBJECTIVE:

   A. To foster worldwide cooperation on Air Traffic Modeling for separation standards and the joint development and use of these capabilities to support the efforts in operational concepts, procedure development, and system architecture.

   B. To initially focus on an area of mutual need - the development of common models for safety analysis, especially in the areas of separation standards and collision risk.

II.   BACKGROUND:

   A. The joint perspective is that several questions arise with the advent of various new technologies such as SATNAV, Flight Management Systems and data link, and the new emphasis on User Preferred Routings either as a contract or in Free Flight. Chief among the questions is the safe reduction of separation standards. Couple this quest with the relaxation of assigned directional altitudes to the ultimate - cruise climb - and collision risk becomes a significant analytic requirement. Add to this new automation techniques to aid the controller and safety prediction becomes an important consideration. All these are areas where significant improvements need to be made to validate capabilities and speed implementation.

      1.   Separation Standards. Although considerable analysis has gone into oceanic separation standards; domestic standards have evolved more through history than science. Advances in navigation, communication and surveillance technologies, and recent proposals for new operational concepts, have been met with calls to revisit and reduce separation standards. To do this, a consistent acceptable method for ascertaining safety related to separation must be developed and applied.

      2.   Collision Risk. Moves to reduce horizontal separations on approach run full up against an inability to ascertain collision risk. The probability of pilot/aircraft deviation in such a situation are not well understood since they are rare events and there has not been a concerted effort to ascertain what this probability might be.

      3.   Controller Aids. Finally, many of the new automation systems are meant to improve the controller's productivity and assert that they also improve safety. There is currently no uniform way to predict safety implications of technology. This area of investigation would identify existing methods and their use for safety prediction, and coordinate the development of international aviation methods in this area.

B. This is an area where development is still in its infancy and is ripe for cooperative development, to ensure both consistency of measure as well as ensuring complementary rather than parallel development, increasing the net leverage of resources.

III.   SCOPE:

A. Identify the responsible individuals, analysts and model developers in the areas of separation standards and collision risk within the FAA and the European aviation community.

B. Identify small core group to:

- Develop the issues related to this area,
- Identify available documentation related to the issues - copy and disseminate,
- Develop a joint concept paper that provides a framework of critical assumptions and definitions, defines basic relationships and critical parameters, and identifies basic modeling needs, and
- Develop an agenda and schedule a working conference to bring the core group together.

C. Hold a working conference to:

- Finalize the concept paper,
- Identify sub-groups to work on the issues on a continuing basis to assess the present level of safety and develop methods for assessing safety implications arising from future options for operations, and
- Identify modeling needs and identify a sub-group to prepare a plan for joint development to meet these needs.

IV.   SCHEDULE:

A. Reach agreement on an approach   11/96
B. Identify individuals to participate in this endeavor   1/97
C. Draft concept paper completed   5/97
D. Plan agenda, validate and time for the conference   5/97
E. Conference date (for planning purposes)   9/97
F. Develop Conference follow up program   12/97

The first order of business for the program leads was to form European and American teams. The teams consist, in large part, of volunteers who, because of their individual interest in the subject, took on this task in addition to their regular work. As the work progresses it is expected that additional personnel with expertise in areas important to the effort will join the program.

Once initial teams were assembled, a set of modeling criteria was developed to define the scope of the modeling effort. These criteria, presented later in this report, were refined and expanded over time. The modeling criteria are dependent in large part on the safety-related issues that the model(s) should address. As indicated in the Action Plan, these

issues include separation minima, automation aids, satellite navigation, flight management systems, data link, and various relaxations of the current fixed jet route system, from "contract" user-preferred routings, to full "Free Flight," in which the pilot is allowed to change course without notifying ATC (euphemistically termed "instantaneous intent"—the controller first knows of the intent when he/she sees it on the display). There is still much uncertainty as to how and to what extent many of the "Free Flight" concepts will be implemented. Advice was sought from several quarters, and the unanimous opinion was that the modeling effort should not attempt to encompass all possible issues. Thus, we have yet to finalize on a set of issues that the model should address, although all are agreed that one of the criteria must be to restrict the model to only address issues that make economic sense. For example, if no real economic benefit would be gained from reducing horizontal separation minima to less than four nautical miles, then why spend the resources to include such a possibility in the model?

Two other efforts were carried out simultaneously. A list of factors potentially affecting the probability of a midair collision was drafted and continues to be expanded. A bibliography of relevant documents also was begun and continues. Both the list of factors and the bibliography are presented later in this paper.

The next phase of work will concentrate on the modeling approach. A number of issues initially need to be addressed:

- Should the model estimate absolute risk or relative risk?

- What definition of "collision" should be used – how should aircraft be represented (spheres, cylindrical sections, ...)?

- Should the model be of modular construction?

- What role will simulation, mathematical modeling, probabilities, etc. play?

Many of these questions are discussed in this report.

2.0 ESTABLISHING SEPARATION STANDARDS

2.1 SOME HISTORY OF THE DEVELOPMENT OF SEPARATION STANDARDS

There appears to be no official history of the development of separation standards. However some authors, using source materials and institutional memory, provide us with some insight into the past. Section 2.1.1 is excerpted essentially verbatim from References R2.1, R2.2. Another noteworthy source is Reference R2.3.

2.1.1 Early Separation Standards

The early efforts to urge government to enter air safety regulation, of which separation standards are an important part, were not initiated by the government. Aviation historian Nick Komons [R2.4] wrote in 1978, "An increasing number of people were coming to the conclusion in the early 1920s that aviation could not develop into a viable transportation mode without Federal Safety Regulation. These were not concerned citizens seeking safety for safety's sake. These were people within the aviation community − aircraft manufacturers and operators, and others, who, in one way or another, depended, at least in part, on aviation for a livelihood."

Agitation for Federal air safety legislation began more than six years before Calvin Coolidge signed the Air Commerce Act into law in 1926. In 1921, Herbert Hoover wrote, "It is interesting to note that this is the only industry that favors having itself regulated by the government." A Congressional report at the time noted, "Congress has been denounced unsparingly for passing legislation regulating and controlling business...it is rather startling, to say the least to have an industry...asking and urging legislation putting this business completely under Federal control."

Before radar of any kind was used for air traffic control, separation depended on dead-reckoning and pilot reports. The controller, using flight strips to "see" his targets, separated aircraft by feeding them into certain routes with time separation, knowing that known aircraft speeds over the route distance would keep them apart. Pilot reports by radio, when available, were used to update positions. This was called procedural control. Of necessity, separation distances were quite large since little was known about winds aloft and the exact positions, speeds, and directions of the aircraft. Lateral separations on preestablished routes that might intersect were primarily achieved through altitude separation or by longitudinal procedural separation. Visual Flight Rules (VFR) or Visual Meteorological Conditions (VMC) rules, in which the pilot was responsible for maintaining separation by visual contact with other traffic, were widely used.

The earliest standards for air traffic control separation between aircraft, usually for longitudinal spacing, were entirely based on time separation, using best estimates of the aircraft capabilities and environmental vagaries. Early uses of navigation aids, starting with light beacons and later radio beacons, still used time as the basic separation tool.

With the introduction of more sophisticated navigation aids, particularly the VHF Omnidirectional Range (VOR), computations of probable displacement from desired paths were introduced. The FAA, in its air route and separation computations, based them on (and sometimes still uses) a concept of "system use error." It created airway (route) width designations, on a "95 percent containment probability" basis, based on a root-sum-square (RSS) combination of ground station error (at the greatest usable distance from the facility), airborne navigation system and display error, and a pilotage factor. It assumed that the error distributions were normal.

"The first radar-equipped control tower for civilian flying was unveiled at the Indianapolis Airport" in 1946 by the Civil Aeronautics Administration (CAA), a forerunner of the modern Federal Aviation Administration (FAA) [R2.5]. Shortly thereafter, the *Radar Procedures Manual* specified three-mile lateral separation (paragraph 3.611): "the aircraft may be turned toward the desired course by the radar controller and given headings which will keep it at least three miles laterally from all holding aircraft until past the pattern" [R2.6]. At the same time, a two-mile longitudinal separation for aircraft on final approach was allowed (paragraph 3.516). This value may have been initially based, not so much on radar accuracy (which was considered very good), but on the desire to establish a two-mile separation between arrivals to balance runway occupancy times and interarrival separations. Based on the approach speeds of the DC-3s, then in wide use, a two-mile separation would have resulted in an average Inter-Arrival Time (IAT) separation of 72 seconds, thus allowing ample time for an aircraft landing rollout before processing a new arrival. Interestingly enough, a 72-second IAT is still typical today under VMC conditions at large U.S. airport hubs.

By 1949 or 1950, a three-mile horizontal separation "was arrived at in coordination with interested representatives of all users of the Washington National Airport. Its choice was influenced both by considerations of equipment data acquisition, presentation, and interpretation, and by stress and strain of flying the system and of controlling the system" [R2.6]. There was precedent in the military. In the mid-1940s "the air forces [had] established a three-mile radar separation for controlled aircraft based mainly on the idea of keeping blips on the display from merging. It was a function of the radar beam width and equipment resolution at 30 miles ... " [R2.7]. Ultimately, however, "it appeared to be based on a subjective interpretation of the perceived limitations of equipment rather than on an actual need for physical separation of that magnitude. The final figure was a compromise, the controllers suggesting a smaller figure and the pilots a larger one" [R2.8]. (The wake vortex problem was neither well-known, nor well-understood at the time.)

In 1953, the provision for five-mile separation for controlled aircraft that are more than 40 miles from the radar site appeared in the Third Edition of *Radar Procedures for Airport Traffic Control Towers*. As an aside of some interest, a quote from the *United States Manual of Radar Air Traffic Control Procedures* [R2.9] five years later − when the CAA had just become the Federal Aviation *Agency* − reveals something of the status of radar

separation in its early days: "The number of aircraft which will be separated by radar should be kept to a minimum. By so doing, the controller workload is reduced ... . Standard nonradar separation shall be provided to any aircraft whenever requested by the pilot" [R2.9, Section 3.1].

The choice of five miles was almost certainly influenced by the fact that radar target arcs of more distant targets appear wider on the radar screen, and this is almost certainly why a larger separation minimum was deemed necessary for targets sufficiently far from the radar site. However, to many observers there does not appear to have been a precise rationale, at the time, for the three- and five-mile figures.

In fact, an unpublished, unofficial FAA staff study from the early 1970s flatly asserts, "no rationale exists for the broadband radar minima" [R2.10]. That study goes on to develop a rationale pertaining to a "theoretical worst case situation"—one in which radar accuracy with respect to position, and registration with respect to another radar (mosaicing), were at their worst expected levels. A 95-percent probability envelope was computed for each aircraft, and one nautical mile (nmi) was added as "a type of safety valve." (Note that if the positioning errors on the two aircraft are independent, the combined probability envelope is 99.75 percent.)

It should be noted that Terminal Area Instrument Procedures (TERPS) have, for many years, been based on 99.7 percent for aircraft-to-terrain separation vs. the 95 percent for aircraft-to-aircraft separation. Protection against aircraft contact with obstacles and obstructions near airports are dealt with by a series of design standards laid out in FAA Federal Aviation Regulations Part 77, "Objects Affecting Navigable Airspace," which many years of experience have shown to be successful and safe.

The introduction of secondary surveillance radar with its transponder-provided beacon identifiers and altitudes has not, to date, resulted in a reduction of horizontal or vertical separation standards in domestic airspace. The RTCA SC-150 on Reduced Vertical Separation studied the possibility of reducing vertical separation to 1,000 ft. above flight level 290 (FL 290), but concerns about the altimetry accuracy and altitude-maintaining ability of systems in some airplanes, and other issues resulted in no recommendation from the committee.

2.1.2 Target Levels of Safety

One approach to establishing separation standards involves establishment of a "target level of safety," based on rational, numerical analysis. Although total safety is a goal, economic and physical realities require one to accept the possibility of an accident, albeit with a very small probability of occurrence. The approach was first invoked by the British Air Registration Board (ARB), the U.K. certifying authority, in the late 1950s, when the issue of approving an automatic "all-weather" landing system for passenger aircraft arose. James Doolittle had made "blind" landings in 1927, and the French Aero Postale had

safely made blind landings for years, but such capability had not been approved by any country for airliners.

The ARB started by looking at history, establishing the landing accident rate then being achieved. Based on a study of nearly twenty airline landing accidents (mostly propeller aircraft), it found that there had been about one accident for each million landings. It reasoned that introduction of a new capability such as automatic landing would be designed with the intent of improving the safety record, but could, in no event, allow safety to deteriorate. It called for a design that would have a predicted (and, to the extent possible, demonstrated) failure rate of no more than one in ten million landings, ten times better that the rate experienced in normal operations. It imposed the assumption that any failure of the automatic landing system would result in a fatal accident - a pessimistic assertion.

The ARB was aware of another basic point: The kind of analysis it was imposing had little or no value in offering guidance on the absolute safety to be achieved, but it was valuable in comparing the safety value of several alternative approaches. The idea of a target level of safety was attractive and felt philosophically right to many in the industry. It was rooted in the reality of safety actually achieved, based on historical record. Building a realistic goal for improvement was easy and could be based on rational grounds. Application of the target level of safety poses tough problems, not the least of which is the collection of adequate data, but its implication − that any new design, whether it is an engine, flight control system, or wing structure, must be at least as good and hopefully better, than its predecessors − feels right.

Many people and organizations tested the target level of safety idea, especially the target number of one accident in ten million events. A study done by the International Civil Aviation Organization Review of the General Concept of Separation Panel (ICAO RGCSP) in 1975, using UK mortality rates, showed that the risk of mortality in the healthiest age groups was six in ten million person hours. By comparison, 1965-1973 data yielded a value of 10.5 fatal accidents in 10 million flying hours.

ICAO, the U.N. international aviation standard-setting body, published further corroborating information. A comprehensive study by several countries, evaluated fatality rates in manufacturing, railway work, and public road vehicles; mortality rates in the general populations; and a variety of air accidents, from landings to midair collisions. The resulting finding was that an appropriate target level of safety might be between one and six fatal accidents in 10 million flying hours, with the resulting risk appropriately shared among mechanical failure, midair collisions, and other accident causes. This target range seemed credible: It should be used with caution, but it was rational.

2.1.3   Recent Events

Important strides have been made by the FAA in recent years in reducing longitudinal and lateral separations. The case was well described in 1988 by the Airport Associations Coordinating Council (AACC): "...Existing separation standards are highly conservative, as they should be and must be. While they must always be conservative, current standards make little or no distinction between situations where highly sophisticated aircraft/air crew/air traffic service/equipment infrastructures exist, and situations where only basic services may be available. The current separation figures may have been agreed upon, in part to protect against difficulties at airports where the quality of air traffic control may not be as good as might be desirable. It seems to us that a way must be found to provide the highest level of safety protection for all circumstances without putting at a disadvantage airports that have adequate air traffic control service, and which badly need all the capacity that can safely be achieved."

There are large contrasts between separations allowed in practice in different countries and at different airports for such procedures as independent simultaneous instrument flight rules (IFR) approaches to parallel runways, dependent parallel IFR approaches, required IFR longitudinal separations, and converging IFR approaches. Perhaps the most important distinction between U.S. practice and that of many other countries is the use in visual meteorological conditions (VMC) of visual final approaches when the initial approach is in instrument meteorological conditions (IMC). This yields a major capacity benefit.

In its 1988 paper, quoted above, the AACC noted, "...the contrast between the spacings allowed under current U.S. procedures, and the efforts under way to improve on them; and the standards in other parts of the world. Since each of the current U.S. minimums was adopted after lengthy study and testing/demonstration, the data have been available to all, and the safety record achieved with the U.S. standards, in some cases over many years of use, has been superb, they should surely receive sympathetic consideration by ICAO as well."

A successful approach has been used by the FAA (starting in the 1970s) for examining the possibility of reducing separation standards for parallel runways having independent IFR operations. Extensive demonstrations, tests, and consultations among concerned parties and operations experts led to a reduction in the minimum allowable separation between parallel runways. The required spacing has now reached 3,400 ft.

Other factors may affect the safety and acceptability of allowing simultaneous independent approaches to more closely separated parallel runways during IMC:

- More automation in flight control systems that reduce the amount of air space occupied and the impact of missed approaches,

- Automatic warnings of aircraft deviations from assigned paths provided by the ground data acquisition sensor, and

- Special training for pilots who will be making simultaneous approaches.

The introduction of automatic dependent surveillance (ADS) adds a new possibility for reduced separation minima. The accuracy of the system is prospectively very high (100 meters) if Global Positioning System/Global Navigation Satellite System (GPS/GNSS) is used. While the use of satellite navigation may reduce exposure to blunders, the system is "dependent" on aircraft information − it incorporates no independent (terrestrially-based) verification of aircraft position. Where no secondary navigation (e.g., inertial) or surveillance systems are available, failure of the ADS aircraft equipment or the satellite service will eliminate both navigation and surveillance services for all en route aircraft with potentially catastrophic results.

2.2   THE SEPARATION STANDARD ESTABLISHMENT PROCESS

2.2.1   The FAA Separation Standard Establishment Process

Although the FAA Flight Standards Service and the FAA Office of Air Traffic must jointly approve any changes in separation standards in the U.S. National Airspace System (NAS), there apparently is no *formal* certification and approval process for making such changes.

The (informal) process normally begins as the result of a concern: capacity limitations, safety (e.g., Boeing 757 wake vortex-induced accidents), operators' desire to fly more fuel efficient flight paths, etc. Cost/benefit studies are performed, which may include simulating the effects that proposed changes would have on en route and terminal airspace and on airports. Such effects might include changes in the number of potential airspace conflicts, an exceedence of airport capacities, and delays. Real time, human-in-the-loop simulations may be performed to determine how pilots and controllers might react in hazardous situations. Probabilistic analysis might also be used to estimate relative or absolute safety levels. If the issue is one of amelioration of a hazardous safety situation, the National Transportation Safety Board may make a non-binding recommendation.

If the issue is not in need of an immediate response and/or there are questions of equipment specification development, the FAA will likely request that the RTCA (formerly named the Radio Technical Commission for Aeronautics) study the question and related proposals. The RTCA [Internet location: http://www.RTCA.org] acts as a forum for government, manufacturer, operator, pilot, international, and other aviation community entities, which present their views and work together to arrive at a consensus on issues. Special Committees are often formed, with representatives of the concerned entities, to address technical issues, including issues of proposed mandatory standards, such as equipment carriage and specifications. Examples of such Special Committees, are the former SC-150 on Reduced Vertical Separation in En Route Airspace, SC-147 on Traffic Alert and Collision Avoidance (TCAS), SC-181 on Navigation Standards, and SC-184 on

Runway Guard Lights. In certain instances, a Select Committee and Task Force may be formed to provide guidance on a major issue. The most recent example is the RTCA Free Flight Steering Committee and Task Force 3 on Free Flight Implementation.

The RTCA makes recommendations to the FAA, which then makes a decision on whether and how to proceed on the issue. The FAA then normally issues a Notice of Proposed Rule Making (NPRM) and holds hearings, allowing the aviation community and others an opportunity for final comments. An Advanced Notice of Proposed Rule Making (ANPRM) may be published and an operational demonstration may be undertaken before the Notice of Proposed Rule Making is advanced. Changes in airspace and operational rules are implemented on a specific date and time. Regulations requiring new or modified equipment carriage, special inspections of aircraft, additional training, etc. normally allow for a period of time before full compliance is mandatory.

2.2.2   The European Separation Standard Establishment Process

European airspace design and procedures are based on ICAO standards and guidelines defined in various documents including ICAO Doc. 8168-OPS/611 "Procedures for Air Navigation Services, Aircraft Operations." Supplementary procedures promulgated specifically for the European region of ICAO are contained in ICAO Doc. 7030. Standards and Recommended Practices (SARPS) are contained in ICAO Doc. 4444. New procedures are published in each State's Aeronautical Information Publication (AIP).

When a new procedure is proposed it is circulated to each member State for review and potential adoption. Each State may adopt the procedure or prohibit the use of the new procedure within its boundaries and/or by its operators (airlines). The process of review by all States prior to adoption is designed to assure the safety and effectiveness of all new procedures.

List of References

R2.1 Rockman, Mark J., "A Review of the Current Radar Separation Minima and Some Thoughts on Reducing Them," McLean, VA: The MITRE Corporation, Working Note 94W000099, FAA Contract DTFA01-93-C-00001, July 1994.

R2.2 Applied Techno-Management Systems, Inc. (ATMS), "Potential Operational Impacts of GPS with Advanced CNS and ATC Automation Technologies," Falls Church, VA: FAA Contract #DTA01-94-Y-00039, February 9, 1996.

R2.3 Machol, Robert E., "Thirty Years of Modeling Midair Collisions," Institute for Operations Research and the Management Sciences, *Interfaces*, 25:5 September-October 1995 (151-172).

R2.4 Komons, Nick A., *Bonfires to Beacons, Federal Policy Under the Air Commerce Act 1926-1938*, Washington: DOT, FAA, 1978.

R2.5 Briddon, A.E., E.A. Champie, and P.A. Marraine, *FAA Historical Fact Book A Chronology 1926-1971*, Washington: Federal Aviation Administration, 1974.

R2.6 King, M. L., *Radar Separation in the Terminal Area*, informal internal memorandum, ARD-104, Washington: Federal Aviation Administration, November 14, 1974.

R2.7 Conversation between M.L. King and Chester Wintermoyer, as reported in [R2.6].

R2.8 Conversation between M.L. King and Russell Bierman (the author of a paper prepared for the FAA for litigation following an aircraft collision over Staten Island, New York), as reported in [R2.6].

R2.9 *United States Manual of Radar Air Traffic Control Procedures*, Revised First Edition, Washington: Federal Aviation Agency, May 1, 1958.

R2.10 Wolf, Ian G., *Beacon Radar Separation Minima for Jacksonville ARTCC Utilizing Digitized Radar*, Washington: Federal Aviation Administration, Unpublished.

3.0 COLLISION MODELING DEFINITIONS AND RISK METRICS

This section addresses how an aircraft might be represented in a collision risk model and what metrics might be appropriate for measuring collision risk.

3.1 DEFINITIONS

For practical purposes, a collision occurs when two objects attempt to occupy the same volume of air at the same time. It is usually quite difficult to incorporate the exact shape of the objects involved into a collision risk model. One would like to consider these objects as point objects, but the probability that a point object coincides with a given point in space is zero. Thus, when modeling the probability of collision of two objects, one cannot treat both objects as points. While it is possible to treat both objects as shapes in space, it is usually much easier to treat one object as a point and the other as a symmetric volume, and then work with the probability that the point lies within the volume. It is not practical or necessary to draw the volume in the shape of an aircraft. It is only necessary that the probability of the point being in the volume approximates the probability of two aircraft being close enough to cause a collision.

A variety of volumes are used in various models, depending on the mathematical formulation and whether the model is two dimensional or three dimensional. Usually, the simplest form mathematically is a circle or sphere. Some models use boxes or rectangles. The Sector Design and Analysis Tool (SDAT) and the Analytic Risk Blunder Model (ARBM) models use a disc shape, which was derived to approximate the en route separation minima rules. Because aircraft wingspan and length are usually approximately equal and much larger than aircraft height, the disc shape is a reasonable approximation, but other approximations would be quite satisfactory. The same model can use different dimensions for analyzing conflicts or collisions.

The dimensions are very important, as the probability of a point being within the volume is directly proportional to the size of the volume. Doubling the radius of a disc or both horizontal dimensions of a rectangular box, results in a fourfold increase in the probability of a point randomly placed in space being within the solid. Doubling the radius of a sphere or all dimensions of a box or disc, increases the risk estimate by a factor of eight.

For a disc or spherical representation, the average of the two aircraft wingspans[1] is a reasonable estimate for the horizontal radius, for this corresponds to the two aircraft centers being at a distance that would result in wingtips touching, or at least the aircraft possibly interfering in the flight dynamics of each other. Some studies have used a sphere with a radius of 500 feet, which is somewhat generous when one considers that a C-5 Galaxy has a wingspan of 223 feet and a length of 248 feet.

A special problem arises when working with step simulations. In order to determine if a collision occurs, the distance between aircraft centers is computed at each time step.

---

[1] Wingspan measured from wingtip to wingtip.

These steps must be made very close, or the aircraft could step through each other undetected. This analysis approach requires an extremely large number of computations to move the aircraft through space. Some form of continuous simulation or supplementary analytic computations would be needed to ensure that a time step simulation would not miss some collisions or conflicts.

Due to aircraft wake, it is not always necessary to have physical contact to have an accident, or at least to encounter turbulence sufficient to cause passenger injury or worse. Recent experience with reduced vertical separations in the North Atlantic suggest that some aircraft are experiencing significant turbulence problems caused by the wakes of aircraft flying many miles ahead and 1,000 ft. above them. At this time, it is uncertain how best to incorporate aircraft wake into a collision risk model. The strength and location of a wake and its effects on other aircraft are highly dependent on the sizes and weights of the aircraft and on atmospheric conditions. Thus, incorporating wake vortices into a collision risk model can introduce a significant, additional complexity into an already complex model.

3.2 RISK METRICS – WHAT IS AN APPROPRIATE METRIC FOR DEFINING THE RISK OF COLLISION?

Generally speaking, risk can be measured in terms of the chance of an adverse event per unit of some activity. In aviation, there are a number of metrics which may conceivably be used to describe risk. These include the following:

Number of Accidents Number of Fatal Accidents Number of Fatalities	**PER**	Year Aircraft Flying Hour Aircraft Mile Passenger Passenger Hour Passenger Mile Flight Stage Passenger Journey

At any moment, the same level of risk could, given sufficient data, be expressed by a variety of metrics, such as fatal accidents per flight hour, expected number of accidents per calendar year, and fatalities per en route passenger hour. It is stressed "at any moment" because, of course, some metrics will be affected by changes in traffic levels or average passenger loads.

Tables 3-1 and 3-2 illustrate that different metrics can be equated to the same level of risk only when done at a given point in time. Neither table is meant to imply anything about the actual level of collision risk in these areas, which may, of course, differ from the figures shown.

Table 3-1 shows how an assumed risk level of 1.5×10^{-8} fatal accidents per flight hour would differ from region to region when expressed as a yearly chance of an accident. The last two rows of the table demonstrate how the yearly chance of an accident may change over time in the same region for a constant risk per flight hour. Conversely, Table 3-2 shows how the exposure to collision risk per flight hour would differ by region for the same yearly chance of collision, based on 1995 traffic estimates. The figures indicate that if the same yearly chance of collision is maintained from region to region, individuals flying in North Atlantic (NAT) Minimum Navigation Performance Standards (MNPS) airspace will, on average, experience roughly a seven times greater risk of en route collision per hour than will individuals flying in European Civil Aviation Conference (ECAC) airspace; while people flying in the Tasman area will, on average, experience roughly 189 times greater risk than those in ECAC.

For this reason, the sole use of metrics such as the probability of an accident per year are not advisable for expressing collision risk, as they give no indication, by themselves, of the individual's exposure to the risk.

The most commonly used metric for collision risk is "fatal accidents per flight hour." This metric is useful because it enables an individual's exposure to risk to be linked directly to the time spent flying, and it is not influenced by changes in such things as the amount of air traffic or passenger levels. Another risk metric applicable to the individual is fatalities per passenger trip. However, data needed to compute this metric are not as readily available.

However, although the metric of fatal accidents is arguably one of the most appropriate for expressing collision risk, examining the risk expressed in other metrics is advisable and, given sufficient data, is relatively straightforward. For example, if the risk in terms of fatal accidents per flight hour, and the number of flight hours per year, are both known for a given region, then the risk in terms of the chance of seeing an accident on a yearly basis in that region can be derived. This yearly accident rate is of interest as it affects people's perception of their exposure to risk, which in turn can affect their willingness to fly, with obvious commercial implications. This risk measure may also be expressed as a quantity analogous to the reliability theory parameter "Mean Time Between Failures" (MTBF): The Mean (average) Time Between Accidents (MTBA) is just the reciprocal of the average number of accidents per year. For example, for an average of three accidents per year, the MTBA is 1/3 year, or about 122 days.

The choice of a risk metric also depends upon the type of risk one is attempting to measure. For example, for midair collisions en route, an appropriate activity measure would be flight hours. However, for collisions in the terminal environment, a more appropriate measure of activity would be the number of departures and arrivals.

Table 3-1

**Chance of Collision per Year, for Constant Assumed Risk
per Flight Hour, by Region and Year[2]**

Region	Australia (Tasman[3])	North Atlantic MNPS	ECAC
Approximate number of en route commercial flight hours for 1995	30,600	835,500	5,778,000
Assumed level of risk expressed in fatal accidents per flight hr	1.5×10^{-8}	1.5×10^{-8}	1.5×10^{-8}
Assumed level of risk expressed in chance of collision[4] per year, 1995	$\frac{1}{4357}$	$\frac{1}{160}$	$\frac{1}{23}$
Assumed level of risk expressed in chance of collision per year, 2000	$\frac{1}{3565}$	$\frac{1}{116}$	$\frac{1}{19}$

Table 3-2

**Risk per Flight Hour by Region for Constant Assumed Chance
of Collision per Year, Based on 1995 Traffic Estimates**

Assumed Chance of Collision per Year	Collision Risk per Flight Hour		
	Australia (Tasman)	North Atlantic MNPS	ECAC
1/4537	7.2×10^{-9}	2.6×10^{-10}	3.8×10^{-11}
1/160	2.0×10^{-7}	7.4×10^{-9}	1.1×10^{-9}
1/23	1.4×10^{-6}	5.2×10^{-8}	7.5×10^{-9}

The user of the risk metric often determines what is the most appropriate metric. For example, a regulatory, standard-setting authority might consider the number of (fatal)

---

[2] 1995 flight hours, and predicted increase for year 2000, obtained as follows:
  Australian: Personal communication with Australian CAA
  NAT MNPS: NAT Traffic Forecasting Report
  ECAC: Eurocontrol Air Traffic Statistics and Forecasts Doc No 94.80.14

[3] Roughly speaking, the area between 24°S to 44°S and 174°E to 151°E.

[4] It is assumed that one collision equals two fatal accidents.

accidents per mile, departure, flight hour, or year to be the most appropriate metric. A passenger probably would consider an appropriate metric to be the number of fatalities per passenger (origin-to-destination) trip to be most appropriate. Thus, for a passenger, the number of stops en route is of interest, as one's risk of an accident in a terminal environment is roughly proportional to the total number of takeoffs and landings during the trip. For these types of accidents, as the number of intermediate landings increases, the risk measured in terms of accidents per departure might remain relatively constant, but the risk measured in fatal accidents per flight hour, passenger fatalities per flight hour, or passenger fatalities per trip would increase.

The average seating capacity of large air carriers might also affect the value of a risk metric for some types of accidents and types of metrics. To understand this, consider the following, hypothetical situation. Suppose, in the future, all large aircraft were replaced by ones with twice the seating capacity and, as a consequence, half as many flights occur. Then, as explained below, one would expect changes in risk metrics to be approximately as shown in Table 3-3. (It is assumed that the percent of fatalities in a fatal accident is constant for any chosen load factor. In other words, the percent of fatalities in a fatal accident does not change if the seating capacity and the number of occupied seats both double.)

For any single aircraft, the risk of being in a single-aircraft accident would be about the same, but the number of accidents per year would be half as great because only half as many aircraft are flying. Passenger fatalities per year would remain about the same, because while there would be half as many fatal accidents per year, there would be twice as many passengers involved in each accident that occurs. Because there would be the same number of passenger trips per year, the number of fatalities per passenger trip would also remain the same.

While the number of passenger fatalities per year would remain the same, the number of flight hours and departures would halve. Hence the number of passenger fatalities per flight hour and per departure would double!

The situation for midair collisions is different. Most analyses suggest that the probability of a midair collision is roughly proportional to the square of the number of aircraft in a given airspace region. With half as many aircraft flying, one expects the number of midair collisions per year to be about 1/4 the present number. Since there would be about 1/4 as many collisions and half as many departures and flight hours, the number of midair collisions per flight hour or per departure would be about half. Since there would be twice as many passengers per airplane, but 1/4 as many midair collisions, the number of passenger fatalities per year in midair collisions would be about half the present number. The number of passenger trips per year would remain the same, so the number of fatalities in midair collisions per passenger trip would be about half. With half as many fatalities per year and half as many flight hours and departures per year, the number of fatalities per flight hour or per departure would remain about the same.

Table 3-3

Changes in Risk Metrics if Aircraft Capacities Double but Number of Flights Halve

Metric	Change
Single-aircraft fatal accidents per flight hour or per departure	No change (assumed)
Single-aircraft fatal accidents per year	Half of current rate
Passenger fatalities in single-aircraft fatal accidents per passenger trip or per year	No change
Passenger fatalities in single-aircraft fatal accidents per flight hour or per departure	Double the current rate
Midair collisions per year	Approximately 1/4 current rate
Midair collisions per flight hour or per departure	Approximately half of current rate
Fatalities in midair collisions per year or per passenger trip	Approximately half the current rate
Fatalities in midair collisions per flight hour or per departure	Approximately the same

3.3   THE ACCEPTABILITY OF RISK

In assessing the acceptability of risk, a number of industries (e.g., nuclear) now use an approach known as the As-Low-As-Reasonably-Practicable (ALARP) approach. Studies are currently underway within EUROCONTROL to investigate the feasibility of adapting the ALARP approach for use in assessing midair collision risk.

As illustrated in Figure 3-1, risk, in this approach, is classified as being in one of three categories: intolerable, tolerable if ALARP, and negligible.

- If a system's risk falls into the intolerable category, then action must be taken to redress this. If this is not possible, the system should be halted or not implemented.

- If a system's risk falls into the tolerable category, it must be proven to be as low as reasonably practicable within that region for the system to be considered acceptable. Showing a system is ALARP means demonstrating that any further risk reduction in the tolerable zone is either impracticable or grossly out-weighed by the costs.

- If a system's risk falls into the negligible category, no action is required other than monitoring to ensure that the negligible risk is maintained.

With the ALARP approach, the boundary lines between the risk categories negligible, tolerable, and intolerable need to be specified; they are not automatically set. Also, it is important that the risks from a given activity are shown to be within the negligible or tolerable regions from both an individual and societal point of view. It is well known that the public is willing to accept much higher risks in many other activities than in aviation.
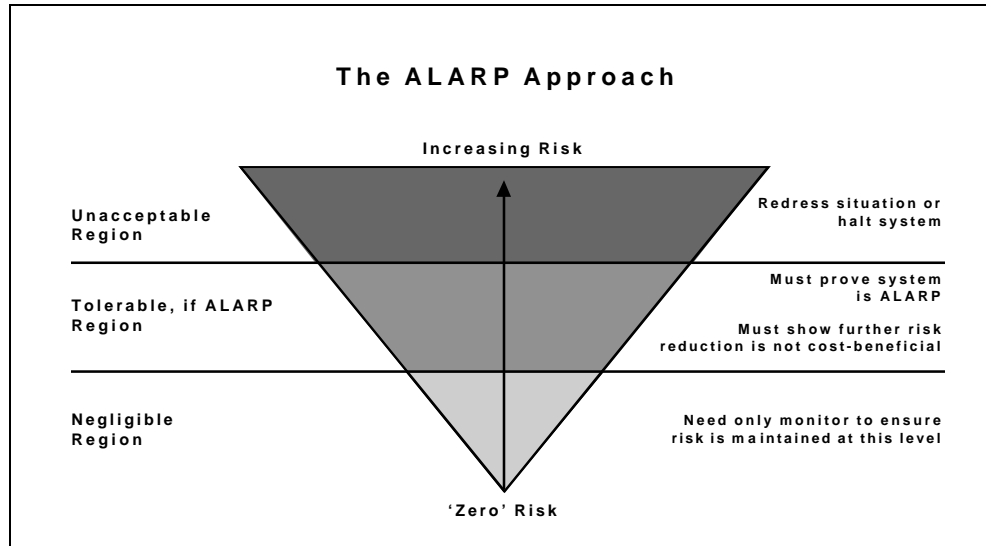
Figure 3-1. ALARP Approach

It could be argued that the risk of midair collision should also be examined in such way. That is, the risk should be expressed both as a metric that can easily be related to the individual risk (e.g., fatal accident per flight hour) and as a metric which can be easily related to the societal risk (e.g., risk of collision per year or MTBA). In using this approach, it is necessary to take into account that collision risk is only a small part of the overall risk from flying.

Reference

The following reference includes a thorough study of the available literature on safety analysis, metrics, and validation techniques. An appendix also includes descriptions of most available tools for evaluating safety, capacity, and human factors.

"GENOVA Work Package 3 Report, Version 1, Methods and Techniques," European Union DG VII, Contract No. AT-95-SC.112, NLR, 1997. [GENOVA = Generic Overall Validation for ATM.]

[This page intentionally blank]

4.0 MODELING CRITERIA

This section presents criteria that have been suggested as a means of bounding the scope of this modeling effort. Among those criteria is one which suggests that before modeling the safety effects of some change in current air traffic systems, one should perform an analysis to determine if such a change would result in economic benefit. Section 4.2 presents a discussion of some of the factors that must be considered in analyzing what benefits might be derivable from reduced separation minima (standards) and suggests an approach to estimating how much increased capacity might be derived from reduced separation minima.

4.1 LIST OF CRITERIA

There is a need for criteria to define and bound the scope of the task. The criteria currently adhered to are as follows:

a) An economic analysis should be performed to determine if any real benefit will gained from a potential change. Realistically, will there be a real economic benefit from reducing horizontal or vertical separation? If the economic benefit is slight or nonexistent, there is no reason to reduce separation minima or engage in a major collision risk modeling effort. (This is discussed in Section 4.2.)

b) Concentrate on en route at this, first stage, with terminal airspace to follow.

c) Consider separation between aircraft (aircraft-to-aircraft separation maintenance as opposed to, for example, separation between jet ways).

d) Assume that some surveillance infrastructure will continue to be required, that is, separation will not be guaranteed solely by aircraft navigational performance or aircraft-to-aircraft means. This may or may not involve ground infrastructure. In particular, it is assumed that in the foreseeable future, controllers will be responsible for detecting and alerting pilots to a pending loss of IFR separation, and issuing them guidance on how to maintain separation/avoid a collision.

e) Human performance (pilot and controller capabilities, reliability, workload, errors, etc.) must be included in any collision risk modeling.

f) Any assumptions of independence of systems, operations, or failure modes must be thoroughly scrutinized. For example, could a third factor, such as inadequate management, cause two, seemingly independent factors to be dependent or statistically correlated?

g) Information from accident and incident reports, including operational error and pilot deviation reports, should be used. These reports can yield qualitative, if not

quantitative, information on what can happen in the "tails" of "human performance distributions."

h) Consideration should be given to aircraft performance characteristics including wake vortex generation and its potential effect on neighboring aircraft. Lack of understanding of wake vortex phenomena may result in controllers and pilots applying larger-than-necessary safety buffers in-trail to avoid negative wake vortex effects during the approach phase of flight. Wake vortex encounters could well occur in future en route airspace scenarios if separation minima (vertical or horizontal) are reduced.

DISCUSSION:

The following paragraphs provide some of the background that led to these criteria. The paragraph numbering corresponds to that above.

a) Safety modeling in en route airspace is quite complex, time consuming, resource intensive, and data intensive. It is, therefore, wise to determine in advance what really needs to be modeled. For example, if a rule is being considered that would allow pilots to change course in a non-emergency without prior approval from Air Traffic Control (ATC), it would be prudent to determine first whether such a rule would be beneficial before embarking on an effort to include such a possibility in a safety model.

b) The decision to concentrate on en route airspace first is primarily due to the belief that collision risk will be simpler to model in en route airspace than in terminal airspace. Also, there are some ongoing efforts to model certain types of terminal airspace, such as simultaneous parallel approaches, whereas we are unaware of any substantial effort to model collision risk in en route airspace.

c) The beginnings of user-preferred routing are already in place with the FAA's National Route Program. It is expected that this philosophy of a more "free" airspace will be expanded in the future. European airspace is expected to continue to have some fixed routing, but it will also have some relaxation of fixed routing. Thus, it is necessary to develop a model that can include various geometries of aircraft trajectories, as well as changes in those geometries. It appears that this can be most easily accomplished with a model that addresses aircraft-to-aircraft separation—one that will be applicable whatever trajectory geometries might exist.

d) It is the opinion of the team participants that a high level of airspace safety and efficiency can only be maintained if some form of aircraft/airspace surveillance is present, independent of pilots. It is also believed that, at present, this surveillance cannot be adequately accomplished solely by means of on-board automated systems, but will require oversight by air traffic controllers.

e) Separation distances in en route and terminal airspace are much less than in oceanic airspace. A controller error, pilot blunder, or malfunctioning avionics engenders a much higher risk of collision when separations are small. Thus, in addition to modeling the likelihood and effects of pilot and controller errors in initially causing a loss of separation, the ability of pilots and controllers to recognize that a loss of separation exists and to appropriately respond must be modeled, as must be the responsiveness of aircraft in emergency maneuvers.

Human interactions with equipment must also be considered. For example, a blunder might be the entering of incorrect information into a flight computer, or the response to an automated warning might be inappropriate or delayed.

f) The high level of safety in the National Airspace System (NAS) is due to redundancies in the system. For these redundancies to be truly effective they should be independent, that is, the failure of one should not affect the probability of the failure of another. Often redundant equipment, procedures, etc. are treated as being independent when, in fact, the existence of another factor may impact all of them. Assumptions of independence must, therefore, be scrutinized thoroughly when combining the probabilities of system failures.

g) The relative infrequency of airspace incidents and accidents precludes using data on these events to generate probability distributions with any degree of accuracy. However, the narratives of these events provide very useful qualitative information on what can go wrong and how pilots and controllers react in such circumstances. These narratives also give some insight into how different factors might interact in unexpected ways.

h) Consideration should be given to more realistic modeling of aircraft performance. Aircraft technology (including navigation and general aircraft performance characteristics) has changed significantly in the past 30 years, warranting a more accurate modeling of the aircraft maneuvering envelopes in the en route flight phase. Given that aircraft have very limited maneuvering envelopes at cruising conditions, it is important to include aircraft performance as a constraint variable in any future collision risk model.

Wake vortices at high altitude and in the clean aircraft configuration are not well understood. Nevertheless, there is sufficient anecdotal experience to suggest that this factor might well play a role in future separation criteria applied to the en route system. The team should identify possible avenues to model wake vortex as an exogenous factor. There are several macroscopic wake vortex behavior models developed by NASA that perhaps could serve as the basis of a modeling approach.

4.2 CONSIDERATIONS IN DETERMINING THE BENEFITS OF REDUCED SEPARATION MINIMA

4.2.1 Potential Benefits of Reducing Separation Standards

A primary benefit that could be claimed for reducing separation minima in en route airspace is increased airspace capacity. Increased capacity relates to greater aircraft throughput and reduced delay, with consequent greater fuel efficiency. The questions are: 1) will reduced separation requirements actually improve airspace capacity, and 2) if so, will this accrue to increased throughput and reduced delay in the entire NAS, or will other bottlenecks in the system (e.g., limited airport and terminal airspace capacity) impose restrictions that will cancel these benefits. If this is the case, the result may be that more airplanes get through the en route airspace more quickly and fuel efficiently only to spend more time in the terminal airspace or the feeder sectors.

4.2.2 Impact on Sector Capacity

Airspace capacity is limited not only by its usable/useful volume, but also by the workload capacity of the controller. A controller team manning a sector can only provide service to a given number of aircraft per unit of time, even though there may be enough airspace to physically contain many additional aircraft while maintaining the required separation between them. A way to overcome this problem is to divide the airspace into a greater number of sectors. However, this is not a desirable solution as it requires more controllers, more ATC equipment, more radio frequencies, and more work for the aircrews in changing frequencies as they pass through more sectors.

Controller workload consists of much more than separation assurance. Each aircraft must be radio contacted and radar identified. Aircraft must be given clearances and headings to properly guide them through the airspace. They must be given hand-offs to other controller teams as they approach sector boundaries. These are a few of the routine items that are required even if there are no other aircraft to be considered.

On the other hand, as the number of aircraft controlled by the sector increases and as user preferred routing becomes prevalent, controller workload may increase out of proportion to the number of aircraft. Surveillance must be maintained on each to insure that other aircraft are not potential collision threats. Controllers currently maintain aircraft at horizontal separations greater than today's minima. If separation minima are decreased, controllers are likely to maintain aircraft at horizontal separations greater than the new minima to ensure adequate warning time. These actual separations may be smaller than those maintained today, depending on controller workload and airspace complexity.

One of the tools available to analyze controller workload is the FAA's Sector Design Analysis Tool (SDAT). SDAT provides data on the workload associated with a historical sample of traffic data. It translates data recorded as controller/HOST messages in Systems Analysis Recording (SAR) data into over a hundred different controller actions,

either specifically identified in the data, or inferred from radar track data. The expected number of required separation assurance actions is determined from a probabilistic analysis of the observed track data. SDAT has an assigned number of seconds to complete each action, and the total number of work seconds is plotted and summed over the sample period.

A sample of SAR data for a selected group of sectors over a number of busy periods can be used to estimate the amount of work (i.e., aircraft handled without error) that a controller team can accomplish in a given period of time in each sector. This can be related to workload capacity for a given mix of traffic.

Assuming that separation distances are reduced for a historical sample of traffic, the revised separation assurance workload can be re-computed using SDAT and the resulting impact on total workload can thus be estimated. This will provide an estimate of how reduced separation requirements will affect controllers' ability in a specific sector to handle increased numbers of aircraft. This process must be repeated for a number of different sectors of different types to obtain a complete picture of the effects of reduced separation.

It is vital that information be obtained from working controllers regarding the factors that should be considered in determining the impacts of reduced separations and the controllers own expectations of what those impacts would be. Both face-to-face exchanges with controllers and a survey could be conducted. The survey should include problem sectors, namely those that are frequently determined to be "red sectors" in the monitor alert, and/or those that experience a high number of operational errors. This could provide valuable insights to guide the analysis.

There are a number of controller work actions not captured in the SAR messages that should be considered. One is the assistance given to airline pilots seeking to change altitude to reduce turbulence. Although this is an optional service, it does occupy a significant amount of a controller's time.

4.2.3 Impact on Total NAS Capacity

Aircraft delay can be defined as the time required for an aircraft to fly from gate-to-gate minus the time the flight would have taken in the absence of restrictions imposed by the NAS. These restrictions can include those resulting from airport and airspace congestion, adverse weather, noise abatement procedures, airspace restrictions, etc. Delay due to weather is referred to as weather-related delay, and the like.

To estimate the potential reduced delay benefit resulting from reduced separation, all restrictions that currently exist can be assumed to remain in force except for any increase in sector capacity resulting from the reduced separation. A delay model that is capable of relating a postulated increase in sector capacity to the total NAS capacity, including the

effect of limited airport and terminal airspace capacity, is needed. It is yet to be determined whether any existing model has this capability.

Consider, for example, the National Airspace Simulation Performance Capability (NASPAC), a model that considers both airport and sector capacity. Sector capacity is modeled as both an instantaneous airborne aircraft capacity and as an hourly throughput capacity. Airport capacity is measured as an hourly throughput value that is dependent on the arrival/departure mix.

It is uncertain, however, whether NASPAC will have the capability to determine how limitations on airport capacity impact improved en route airspace capacity. This model could perhaps provide a first order approximation to the NAS capacity issue. This analysis will be particularly challenging for NASPAC as future collision risk modeling scenarios will likely involve aircraft-to-aircraft separations instead of the typical airway-to-airway separations. Given NASPAC's flight route definition structure, i.e., predefined link-node structure elements, it is possible to speculate that Free Flight operations probably will be represented at a medium level of detail in this model. NASPAC will have to be examined more closely to see if it can adequately perform this task.

Developing input data requires significant effort. Sector capacities currently used in NASPAC have been derived from operational values used for traffic flow purposes. They have not been validated, nor do they consider the mix of traffic or weather conditions. A detailed study of how reduced separation minima affect airspace capacity could be conducted, using, for example, SDAT, with the SDAT output then used in NASPAC. This is feasible only on a sample basis of several centers over several hours. But it would provide a reasonable estimate of the kind of benefits that would accrue in total system capacity through reduced separation minima.

Other models that could be considered for use in this analysis include the Reorganized ATC Mathematical Simulator (RAMS), the National Airspace Resource Investment Model (NARIM), SIMMOD (the FAA's Airport/Airspace Simulation Model), and the Total Airspace and Airport Modeller (TAAM). These models are briefly described in the following paragraphs.

RAMS, a model developed under the auspices of Eurocontrol, is perhaps better suited to model Free Flight operations including aircraft-to-aircraft interactions. However, RAMS will need to be examined for adequacy in this modeling process, because it lacks a detailed representation of the airport resource infrastructure — only runway resources are represented in the model and those with little detail. For a macroscopic view of NAS en route operations, this limitation should not prevent the use of RAMS to gain insight about capacity enhancements derived from reduced separations in a Free Flight structure.

SIMMOD, the FAA airspace and airfield simulation model, might also be capable of estimating capacity and delay changes in NAS once separation criteria are modified. This model is better suited for regional analyses and could, in principle, include a detailed

description of airspace and airports. SIMMOD, however, has many of the same limitations as NASPAC in modeling Free Flight operations given its rigid link-node structure of depicting flight paths. Further analysis will have to be conducted to test whether or not this model is suitable for this collision risk study.

TAAM, the Total Airspace and Airport Modeller, is a tool developed by The Preston Group Ltd., an Australian company based in Melbourne, Victoria. TAAM is described as a full "gate-to-gate" model capable of modelling a complete flight in 4D. It includes capabilities for modeling "Free Flight" scenarios and has a sophisticated conflict detection algorithm, as well as a flexible rule-based expert system for conflict resolution. This tool has been used in a number of "Free Flight" and collision risk studies by government and private organizations, and is used in studies to improve ground/airborne operations and in AT planning. A Beta Version 3, which corrects some problems in the previous version, is currently being tested.

NARIM, the National Airspace Resource Investment Model, contains an operational component that also can be used in capacity and related studies. A fuller description of this model is presented in Chapter 6.

Regardless of the model used to assess benefits and costs of reduced separation in en route airspace, it is important to recognize that almost all of the capacity and delay models available today will have to be tailored to address the needs of this working group.

[This page intentionally blank.]

5.0   APPROACHES TO COLLISION RISK ANALYSIS

5.1   INTRODUCTION

Collision risk modeling for air transportation was initially developed in the 1960s to address the safety of proposed separation standard reductions in the North Atlantic Organized Track Structure (NAT OTS). The methodology developed focused on the environment of oceanic operations, out of range of radar surveillance.   In this environment, safety assurance is dependent on planned or procedural separations, periodic HF (high frequency) voice position reporting, reliable navigation, and large separations. The collision risk modeling effort culminated in the development and acceptance of the so-called Reich Model [R5.1, R5.2] which is still in use today. A history of the early developments and applications of risk modeling can be found in the survey of Machol [R5.3]. The most recent application of the Reich Model has been to develop technical requirements for the Required Vertical Separation Minima (RVSM) for application in the North Atlantic Minimum Performance Standards (MNPS) airspace.

While the Reich Model provides a widely accepted tool for evaluation of collision risk in its intended environment, a number of shortcomings of the methodology have been acknowledged. The model uses convolutions of distributions (including "heavy tailed" double exponential distributions) representing "expected" deviations (due to flight technical errors, allowable inaccuracies in navigation equipment, etc.) and "unexpected" deviations (due to pilot blunders, avionics failures, etc.).

Difficulties in the application of the Reich Model include: (1) the assumption of fixed, usually parallel track operations, (2) the exclusion of communication, surveillance and ATC "control loop" performance, and (3) difficulty in modeling the "tails" of navigation system performance and pilot blunders, where human errors and equipment problems often dominate an infrequently observed population.   The Reich Model emphasizes navigation performance. Its representation of "abnormal/unmodeled" operations, and its empirical as opposed to predictive nature, have also been criticized. The ICAO Required General Concept of Separation Panel (RGCSP) requires collision risk assessments as well as operational evaluations of proposed separation standard changes.

For controlled airspace, great care must be taken in developing deviation distributions based on empirical data. The empirical data includes the effects of air traffic control intervention. "Factoring out" these interventions and relating them to separation minima will require insightful and ingenious analysis.

Recent pressure with the development of the ICAO FANS concept and ICAO's endorsement of Automatic Dependent Surveillance and satellite navigation and communication systems require the timely development of risk methodologies that consider the full range of communications, navigation, and surveillance performance factors. Methodologies that evaluate the ATC control loop, model various kinds of airspace geometry, and are predictive in nature, minimizing the standards development

data-taking time period (to enable the return in investments), are key to operator investment in new technology.

Professors Simpson and Ausrotas [R5.4] outline the difficulties in evaluating risk in ATC operations which have ground intervention. They propose a risk analysis framework for evaluating such operations: "The risk analysis is needed to provide an indication of the benefits of introducing intervention processes which use improved surveillance and communications, and improved decision support for controller intervention." They introduce the concepts of Conformance Management and Hazard Management for reducing the risk of loss of planned separation in an intervention environment.

The following material summarizes alternative methods and models for assessing risk in an ATC environment with intervention. It begins with a review of hazard analysis techniques which have been used to assess risk in complex systems, and whose application to the ATC separation problem is just beginning. These methods should be considered as additional tools for risk modeling, which may be viewed as complimentary to the more typically applied collision risk modeling and simulation tools identified later in this section.

The Collision Risk Modeling (CRM) approach emphasizes empirical (statistical) modeling, navigation performance, and spatial distributions. The Reich Model is the widely used CRM for oceanic parallel track operations. The Hazard Analysis approach tends to have applicability to analytic modeling, communications, surveillance and control-loop performance, and temporal/event representations. Recent experience with collision risk modeling for the North Atlantic has suggested an approach which begins to combine the classical Reich approach with the hazard analysis approach [R5.5]. The Review of the North Atlantic Lateral Collision Risk Model suggests the decomposition of the error terms into specific error categories (which could be based on a functional hazard assessment).

The ICAO Review of the General Concept of Separation Panel (RGCSP) is developing a Manual on Airspace Planning Methodology for the Determination of Separation Minima [R5.6]. The Manual identifies the factors impacting separation minima (Chapter 3) and the methodology for evaluating safety (Chapter 6). Steps in the safety evaluation process include the proposed system definition, setting evaluation criteria, identification of hazards, hazard frequency estimation, consequence modeling, risk estimation, risk evaluation, risk reduction measures, and implementation/monitoring. Both collision risk modeling and hazard/risk analysis methods are identified as risk analysis tools.

5.2   HAZARD ANALYSIS TECHNIQUES APPLIED TO COLLISION RISK

The application of hazard analysis techniques to the development and certification of complex aircraft systems has been used by the industry for several decades. The application of these methods to the problem of loss of separation risk in the ATC system is now under development. RTCA SC-189/EUROCAE WG-53, Air Traffic Services Safety and Interoperability Requirements committee/working group, has a charter to advance CNS/ATM concepts and support operational implementation by developing guidance

material to define safety requirements and inter-operability requirements for Air Traffic Services (ATS) supported by communications [R5.7].

Key issues for the application of hazard analysis techniques include the need for an end-to-end system definition, as well as development of a detailed operational concept for the system applications. The methodology requires allocation of requirements across air, ground, and satellite systems to achieve high-level performance requirements, including airspace use accuracy, system availability, and integrity. The ATS Safety and Inter-operability analysis for SC-189/WG-53 includes the development of "Characteristics of the CNS/ATM Operational Environment for ATS that Use Data Communications" [R5.8]. The document is intended to provide a template for regional planning groups, CAAs (civil aviation authorities), ATS providers, and airspace users to assemble the needed information and definition of safety objectives. Environment characteristics are identified; airspace characteristics enumerated; required functions and capabilities characterized; and operational scenarios developed. This document provides a framework for application of hazard analysis techniques to communications systems.

It may be worthwhile to use hazard analysis to attempt to develop a probability distribution for deviations resulting from the "unexpected" events mentioned previously. Great care will be needed to include all significant events and to accurately determine the probabilities of these events. Existing data may, of course, make this impossible, so that use of a hazard analysis to produce a probability distribution of deviations may result in a distribution that is no more accurate than one developed from empirical data.

A range of hazard analysis tools have been developed and applied to complex system risk evaluation. These are described in Section 5.2.1. Applications of hazard analysis methods, such as fault and event tree analyses to air traffic separation risk evaluation, is summarized in Section 5.2.2.

5.2.1   A Brief Review of Existing Hazard Analysis Techniques

Hazard analysis techniques are divided into four families: the Hazard Identification Family, the Static Assessment Family, the Dynamic Assessment Family, and the Human Reliability Family. Each of these families have techniques which can be applied to the safety evaluation of particular subsystems of the collision risk analysis system for a given application. The right methodology to perform a collision risk analysis may, in fact, be based on a combination of several of these techniques.

The Hazard Identification Family consists of techniques used to systematically identify hazards. These techniques can be employed in the context of collision risk to predict, identify, and/or diagnose what in the system or the procedures may create a collision risk. All the techniques in this family are qualitative and deductive, and do not take dependencies into account. However, their application will be useful preparatory work for applying techniques from the other families. In particular, Preliminary Hazard Analysis (PHA) identifies hazardous conditions or accident scenarios, as well as hazard causes,

effects, and corrective actions. It is, thus, a good starting point in a collision risk analysis. Failure Modes and Effects Analysis (FMEA) provides a systematic approach for analyzing failure modes and their effects. It is usually applied after a PHA and before more sophisticated techniques. This technique could clearly be applied in the equipment portion of a collision risk model/analysis. While FMEA applies to component (both hardware and software), Functional Hazard Analysis (FHA) assesses the effects of functional failures on the system. Finally Hazard and Operability Study (HazOp) takes into account human operations, and could be applied to the human factors part of a collision risk model/analysis.

The Static Assessment Family includes qualitative and quantitative techniques which do not incorporate any dynamics. The most famous techniques in this family are Fault Tree Analysis (FTA) and Event Tree Analysis (ETA).

In a Fault Tree Analysis, a failure or fault of interest (top event) is defined, and faults or failures of components or subsystems which lead to the top event are identified. The failure is often that of a complex system, comprised of sub-systems, components, and human operators. The top event may also be the failure of a single component or even the degradation of performance of an operator or human error. The cause sequence(s) leading to the top event are modeled through a graph where links between failures and/or operational errors are Boolean operators, such as logical AND/OR gates. At any level, an AND gate means that the fault (event) occurs if all of the connected subsystems (immediately below) fail, while with an OR gate, the fault occurs if at least one of the subsystems (immediately below) fails. This type of modeling easily allows for the quantification of the risk of failure by the assignment of a probability of occurrence to each event failure and/or operator action/error at the bottom of the tree. Probabilities then add (OR gates) or multiply (AND gates) when evaluating the probability of the next higher-level event on the tree. This technique assumes independence of the events at each level of the tree. Dependencies can only be included by incorporating them within the definition of an event. Often, risk estimation in complex systems is mis-estimated due to the existence of significant unidentified dependencies. Another limitation of this technique is the lack of dynamics: the relationships of the tree events are assumed to remain unchanged with time.

An important notion in a fault tree is that of the *minimal cut set*, which is the smallest set of elements such that the system fails (i.e., the top event occurs) if each of the elements fail. This technique gives a quick view of the possible faults and critical paths of the system. The main drawbacks of FTA are that failures are assumed to be binary with no time dependency, and that the analysis does not consider the order of occurrence of events at any level of the tree — sequential dependency cannot be coped with (in others words, there is no chronological order of failure occurrences).

On the other hand, an Event Tree Analysis models the possible consequences of a given hazardous situation (the *initiating event)*. It is, thus, generally used in developing measures to minimize the consequences of a hazardous situation. An Event Tree Analysis

is usually represented by branches and generic systems. A generic system is a system or a function which is designed to reduce the effect of the initiating event, and branches represent the functioning or malfunctioning of the generic system. The tree starts with the initiating event, the hazardous situation, from which two branches corresponding to the functioning/malfunctioning of the first generic system are drawn. Each branch is then split in two to represent the effect of the second generic system, and so on.... When the functioning or malfunctioning of any generic system does not influence further consequences, the branch is terminated. When completed, the tree shows how the different systems are influenced by the initiating event and the final outcome of the functioning/malfunctioning of all the generic systems. As in the FTA, only binary events can be modeled, and only non-recoverable generic event sequences with non-recoverable initiating events can be described.

Other techniques such as Cause Consequence Diagrams, Probabilistic Safety Assessment, and Reliability Block Diagrams, all based on FTA or ETA, also belong to this family. The application of FTA and ETA to collision risk is detailed later in Section 5.2.2.

The Dynamic Assessment Family comprises techniques which can deal with temporal relationships and model systems where time has an influence on the system behavior. Examples of these techniques are Discrete State Space Graphs (DSSG), Monte Carlo Simulations, Discrete Event Simulations, Dynamic Event Tree Analysis, and Hybrid-State Markov Processes. DSSG models the behavior of a system and its failures by modeling its discrete states (functional or degraded). States are represented by circles, and transitions between states by arrows. Depending on the types of distributions of duration times in the states, analytical expressions may be available for quantification of the state probabilities. Monte Carlo Simulation allows the construction of a pattern of system responses to an initiating event. Discrete Event Simulation is another simulation technique to obtain system responses to an initiating event. However, unlike Monte Carlo simulations, it does not require expressions for the transition probabilities, but rather a "what-if" description of the system components. Dynamic Event Tree Analysis is an analytical technique which uses the probabilistic and physical behavior of a dynamic process for reliability analysis. The analysis is represented by a tree in which branching can occur at arbitrary discrete points in time. The state transition modeling is ruled by ordinary differential equations. Finally, Hybrid-State Markov Processes model quite general systems, as they allow deterministic and stochastic evolution of a system. This approach requires elaborate mathematical techniques for numerical evaluation. It is used in the model TOPAZ developed by NLR (see Chapter 6) [R5.9].

The last group, the Human Reliability Family, consists of techniques that account for human factors. These techniques are helpful in the context of collision risk analysis, where pilots and controllers play major roles. This family includes Action Error Analysis (AEA), Human Error Assessment and Reduction Technique (HEART), Technique for Human Error Rate Prediction (THERP), Human Interaction Timeline (HITLINE), Operator Action Trees (OATS), Human Cognitive Reliability model (HCR), Empirical Technique to Estimate Operator Errors (TESEO), Absolute Probability Judgment (APJ), Paired

Comparisons (PC), Success Likelihood Index Methodology (SLIM), and Influence Diagram Approach (IDA).

AEA is a technique to study potential mistakes in individual actions, leaving aside human behavior and reasons for mistakes. HEART allows quantification of human errors in operator tasks, while THERP predicts human error probabilities and evaluates the degradation of man-machine systems caused by or connected to human errors. HITLINE is a methodology to incorporate errors of commission in probabilistic assessments; it is well-suited to systematically analyzing operator errors in following emergency operating procedures. In the same line, OATS deals with operator errors during abnormal conditions and provides error types and associated probabilities. HCR, in addition, takes into account skill-based, rule-based, and knowledge-based performance. TESEO evaluates the probability of operator failure, but is more oriented towards comparison between different man-machine systems, rather than absolute probabilities. APJ, PC, and SLIM are all techniques to estimate human error probabilities, and IDA is designed for assessing the dependencies between the influences of the different factors intervening in human reliability.

5.2.2 Some Applications of Hazard Analysis for ATC Systems

A 1996 survey [R5.9, R5.10] identified three studies applying hazard analysis techniques to en route ATM. The first one is due to Fota [R5.11], the second one to the UK CAA [R5.12, R5.13, R5.14], and the third one to Smith [R5.15]. Fota's work is a global safety analysis study of an ATC en route center. Event Tree Analysis is combined with Fault Tree Analysis to perform a Probabilistic Safety Assessment of the en route center. This study is not directed towards a collision risk analysis, but part of the results obtained might be used for the safety assessment of the subsystems forming a collision risk model/analysis. The UK CAA study also provides a PSA of en route air traffic operations. It makes use, in particular, of Preliminary Hazard Identification, Failure Mode and Effect Analysis, and Hazard Identification (a variation on HazOp) to identify human errors and equipment failures in two upper airspace sectors. A Fault Tree Analysis is then performed, starting with the loss of air traffic control as a top event. The Human Error Assessment and Reduction Technique is also used in the fault tree to quantify human errors. Finally, the midair collision probability is estimated from the probability of loss of air traffic control, the probability of failure of some equipment (ACAS), and the probability of a midair collision given an ATC and ACAS failure (obtained from a collision risk model based on a simple scenario). This study illustrates how classical hazard analysis techniques may be applied to subsystems of a complex, man-in-the-loop system, and then combined to obtain the collision risk. The Smith study [R5.15] also performs an FTA and ETA, in a simpler way, on en route ATM situations. Some of the methodologies and results used in these three studies can probably be used in developing a collision risk model/analysis methods for intervention ATC environments. Detailed examples of FTA and ETA applied to en route ATM, and, to some extent, to collision risk can be found in [R5.9, R5.10].

The Reduced Aircraft Separation Risk Assessment Model (RASRAM) is another ATC-related FTA [R5.16]. In this case, the application is the evaluation of risk for reduced terminal area separations, including parallel approach operations. Fault tree models are constructed that represent two collision risk scenarios: 1) In-Trail Separation, and 2) Lateral Separation. The In-Trail scenario is subdivided into Runway Occupancy and Wake Vortex Encounter scenarios. For the Lateral Separation, three possible types of collision risk are posited: collision risk for aircraft on parallel approaches; risk of midair collision following a breakout; and risk of collision with terrain following a breakout. The initial failure event is a "blunder" where one aircraft (Blunder Aircraft) deviates from its approach centerline and crosses a "No Transgression Zone" (NTZ), creating a potentially hazardous condition, namely, a potential collision with the other aircraft (Evader Aircraft). The total lateral separation collision risk (top event of fault tree) is thereby modeled as a hierarchical fault tree structure depicting the various human, equipment, and ATC procedural failures that contribute to the overall collision risk and their respective estimated probability distributions and/or values. Similarly, for the In-Trail collision risk fault tree, the two contributing conditions or scenarios, Simultaneous Runway Occupancy and Wake Vortex Encounter, are modeled as fault trees with operational data acquired from FAA and ICAO.

Although no specific collision risk analysis for en route or terminal airspace has been identified for applying the Event-Sequence Analysis (ESA) methodology to ATC collision risk modeling, other flight operations have been modeled using ESA. For example, an ESA was conducted for determining the risk of a catastrophic accident of a single aircraft during takeoff by delineating the particular series of events which would cause a hazardous takeoff procedure and subsequent accident. This particular ESA, for example, is comprised of a sequence of key events and conditions such as: "First Officer fails to set Flap Lever down during taxi-out," or "Speedbrake/Flap Warning Test is missed during taxi-out," among others, which potentially contribute to an accident during takeoff where the flight crew had failed to move the Flap Handle down prior to takeoff. A similar study focused on the sequence of events which lead to an invalid setting of the engine thrust setting indicator.

5.3   PROBABILISTIC, ANALYTIC MODELS

5.3.1   Probabilistic/Analytic vs. Numerical Simulation Models

The terms "probabilistic model" or "analytic model" are used in this discussion to refer to models that do not employ time-step or event-step numerical simulation (usually with Monte Carlo techniques), but rather use "closed-form" mathematical equations. This discussion concentrates on models of midair collisions applicable to airspace where radar separation is provided, and the question of how reducing horizontal separation minima would affect collision risk.

Some of the advantages of probabilistic models are:

1. Computational efficiency - Numerical simulation models often expend computational effort to produce intermediate values of no interest, e.g., moving aircraft step-by-step through the airspace and computing the distance to all other aircraft at each step. Analytic models tend to get right to the point, making them much more efficient. For many applications this is no longer the advantage that it used to be now that vast computing power is available on almost everyone's desk. However, midair collisions are such rare events that, unless the problem is cleverly decomposed, the number of simulation iterations needed to obtain meaningful results will be enormous.

2. Consistency - Analytic models produce the same answer every time that they are run with the same input data. Monte Carlo (simulation) models will produce different results each time, as a different set of random numbers are drawn. Thus, they must be exercised many times to obtain sufficient statistics. Tests have been developed to determine how many replications are required to assure sufficiently accurate results, but these usually require either an unverifiable assumption about the distribution of the desired statistic or a huge number of replications (based on non-parametric statistics).

3. Clarity - Analytic models generally have fewer logical quirks hidden deep in the computer code that may, under special circumstances, cause unrealistic intermediate results that go undetected. The equations in an analytic model are usually made available for the user to see. This doesn't mean, however, that the equations cannot be faulty or that the software coding of the equations erroneous.

4. Development time - Monte Carlo models are often very complex and costly to program, but probabilistic models can require time-consuming mathematical derivations.

5. Accuracy - When the 'desired' outcome is a very unlikely event (e.g., a midair collision), either a huge number of Monte Carlo trials would be required, or the simulation would require an assumed set of conditions that make the event relatively likely. One must then temper the computed probability with an estimate of the likelihood of these conditions. This is often required in computer modeling, but in the case of collision risk, this will often involve some conditions that are relatively likely combined with others that are orders of magnitude less likely. The analytic approach provides advantages in dealing with combinations of events with a wide range of probabilities.

Some of the disadvantages of probabilistic models are:

1. Limited applicability - Often the problem is far too complex to allow a closed-form solution, or in order to make the problem mathematically tractable, simplifying assumptions have to made that reduce the validity or applicability of the result.

2.   Over simplification - Mathematical equations are generally gross simplifications of reality. If the simplifications eliminate details that are unimportant, this is good; if they cause the desired result to be incorrect, that is a serious drawback. The same can be said about Monte Carlo simulation, but there is a better opportunity in the latter to add complications if they are found to be necessary.

3. Invisibility - Monte Carlo models afford the opportunity to produce graphical or hard-copy intermediate output, allowing the developer and user to observe intermediate results to insure that the model behaves realistically. This is not so easy to do with closed-form models.

4. Dependencies - Analytical models often assume that relationships are straight-forward, whereas they may depend on combinations of factors. For example, there are simple analytic models that are based on average values of the independent variables, whereas relationships might vary non-linearly with these variables. Complex dependencies can be incorporated more easily in a Monte Carlo model, but it is often possible to handle dependencies in a probabilistic model.   Conversely, dependencies are sometimes ignored in Monte Carlo models. Consideration of dependencies in probabilistic models is discussed later in this paper.

Some problems that beset both types of models are:

1. Data unavailability - Both models require data that are often not available.

2. Invalidity - Both types of models are usually not sufficiently validated, if validated at all. To properly validate a model often requires a large effort and special collection of field data independent of the data used to construct the model. The validation should include conditions similar to those for which the model is to be exercised.   For example, the FAA and other organizations have, over the years, built many delay models. Most, if not all, of these have been given a cursory validation, at best. The validation is made under current conditions, and then the model is often used to predict delay under much greater traffic loading and for changed operating conditions, where completely new bottlenecks might, in actuality, appear. If this is true of delay, which is measurable and an everyday occurrence, how much more must it be true of collision risk, which is hard to measure and, fortunately, very rarely observed?

One cannot say that probabilistic models are better than Monte Carlo Models, or vice-versa. Both have advantages and disadvantages. Due to the immense complexity and lack of knowledge of the subject, all are but crude approximations of reality and are likely to produce incorrect results if they are built with incorrect assumptions, contain programming or mathematical errors, are fed incorrect data, and/or are used beyond their range of applicability. In the case of collision risk, when one is dealing with combinations of events and conditions that vary widely in their likelihood, the probabilistic model has an advantage, if it can be constructed with sufficient realism.

5.3.2   Examples of Probabilistic, Collision Risk Models

The Gas Law Model

The simplest analytical collision risk model that has actually been used in FAA studies is the so-called Gas Law Model, which is of the form:

$$N = C * X^2$$

Where

> N = the expected number of midair collisions per year
> C = a constant
> X = the number of aircraft in an area in a given time period

This has been used to justify why a certain device, such as a radar system, is needed in a particular terminal area. The assumption behind this model is that aircraft are completely randomly placed and on random headings, like gas molecules in a bottle. The parameter C was developed by looking at collision statistics in a large number of terminal areas over a large number of years. The annual operations count at the primary airport was used as the parameter X.

This produced very desirable results, in that the radar system was justified. However, there clearly are deficiencies in the methodology. First, aircraft are not distributed randomly in a terminal area. Even if they were so distributed, the model would only make sense if X represented the number of aircraft in the given airspace at the same time. (An aircraft in the airspace on March 1 will not come into conflict with one in the airspace on July 17!) Apparently the value used for C was chosen to "adjust" for using annual operations counts, but as seen in the following example, the "adjustment" was deficient.

The model suggests that the collision risk at Chicago, O'Hare International (ORD) with about 900,000 operations per year would be 300 times as great as Santa Paula (California) Airport (SZP) with about 52,000. But Santa Paula had four midair collisions between 1983 and 1997 (the most for any US airport) while O'Hare had none. Perhaps the operating conditions were not the same at both airports, the aircraft were not really flying randomly (particularly at ORD), and/or the use of annual traffic counts was improper. (A second example is presented in Section 5.3.3.)

The Intersection Model

A complete opposite of the Gas Law Model is the intersection model, which assumes that all aircraft fly on straight-line paths, at constant speed, and in level flight. Because not all aircraft fly from the same origin to the same destination, these paths often cross at (not necessarily published) intersection points. On the face of it, this is a much more realistic model in that aircraft tend to fly fixed routes at constant altitudes for much of the time.

Over very short distances, these paths can be reasonably approximated by constant speed and direction.

If the placement of an aircraft on path 1 can be assumed to be uniformly random (which is reasonable if there is no reason why the aircraft should more likely be at any given point on the path at a given time than any other point), then the probability of a given aircraft on path 2 colliding with the aircraft on path 1 is given by

$$P = 2m_1 R(v_1{}^2 - 2v_1v_2 \cos \emptyset + v_2{}^2)^{\frac{1}{2}} / v_1 v_2 \sin \emptyset \ ,$$

where

P = probability of a given aircraft on path 2 colliding with any one of the
      aircraft on path 1,
$m_{1,2}$ = number of aircraft on path 1 or 2 per hour,
$v_{1,2}$ = velocity of aircraft of aircraft on path 1 or 2 in knots,
R = average size of aircraft in nm.,
$\emptyset$ = (interior) crossing angle in degrees ($0 < \emptyset < 180$).

The model assumes that the aircraft are circles with R equal to the sum of the radii.

If the placement of the aircraft on the paths can be assumed to be independent (which is reasonable in the en route airspace for aircraft going between different origins and destinations), and the traffic densities remain constant, then the expected number of collisions at the intersection can be approximated by

$$N = m_2 P \ .$$

This result was presented by W. Siddiqee in "A Mathematical Model for Predicting the Number of Potential Conflict Situations at Intersecting Air Routes" [R5.17]. This model was developed by assuming that the aircraft are uniformly distributed on their respective paths and that all aircraft on the same path fly the same speed. A similar result might be obtained under other assumptions, so long as the average speeds and the average number of aircraft per hour are used. The model also assumes, as does the Gas Law Model, that there is no intervention, that is, aircraft on collision courses remain on collision courses ("blind flying").

Use of this model does not require the assumption that all aircraft in the airspace are on either of two paths. It can be used repeatedly on a large number of intersections, and for various traffic loadings and speeds.

This model was generalized by K. Geisinger in "Airspace Conflict Equations" [R5.19] to a three dimensional model, allowing either or both paths to be climbing or descending. The aircraft are modeled as discs, with R the sum of the radii and Y the average height of the two aircraft. The paths are also allowed to cross each other with a vertical path

separation, H, at the point of intersection in the horizontal plane. When one or both paths are not level, it is possible to have a collision even when H>Y, because the collision need not occur at that point. The equations are too complex to reproduce here.

These equations were incorporated into the Sector Design Analysis Tool (SDAT), a computer tool for evaluating airspace design. It automatically determines where paths cross, based on actual recorded radar data. The computations are based on separation requirements selected by the user to represent distances at which air traffic control intervention would be either contemplated or provided, to determine air traffic control separation assurance requirements.

The Intersection Model is not the final answer, but it is reasonable enough to provide a partial answer, under a wide variety of cases. It is certainly preferable to a Monte Carlo approach for the cases for which it applies.

An interesting thing to note is that while the Gas Law Model and the Intersection Model are based on completely opposite assumptions about the structure of traffic, they have one important factor in common. They both indicate that collision risk, all other things being equal, is proportional to the square of the traffic level, n. This is common to most other midair collision risk models. This comes from the fact that each of the n aircraft could, in theory, collide with n-1 other aircraft, and thus the number of combinations is

$$C = n \ (n-1)/2$$

which is approximately proportional to the square of n. This suggests that while the number of midair collisions has been very small in the past, the threat will grow out of proportion to the increase in traffic. For example, a 50 percent increase in traffic would correspond to a 125 percent increase in risk, all other things being equal.

5.3.3   Theoretical vs. Empirical Probability Distributions

Empirical Distributions

The above models produce an estimate of a mean value (risk) based on the expected value of the independent variable (traffic density). If one airport had traffic activity that varied much more than another with the same total traffic count, the estimated expected number of collisions would be the same, but the actual risk could be greater. This can be accommodated in a probabilistic model with a sample empirical probability distribution.

For example, consider the Gas Law Model, with an assumed coefficient of $C = 10^{-12}$, applied to a varying traffic load, expressed as an annual rate, following the distribution:

Frequency of Occurrence	Operations per Year	Expected Number of Collisions
0.40	50,000	0.0025
0.30	100,000	0.0100
0.20	200,000	0.0400
0.10	350,000	0.1225
Expected value:	125,000	0.0242

In other words, the airport is operating at a rate of 50,000 operations per year 40 percent of the time, etc. The average rate is 125,000 operations per year. The weighted expected number of collisions per year is 0.0242. This is considerably larger, and presumably more accurate, than the value of 0.0156 that one would obtain from the use of the annual average alone.

A similar approach can be applied to the Intersection Model. Here the aircraft volume can be divided into two streams and expressed in aircraft per hour. As a hypothetical sample, consider an intersection where the internal crossing angle is 168 degrees. Path 1 is level and path 2 descends at 3.2 degrees, passing 20 feet under path 1 at the intersection. The aircraft (B737) on path 1 fly at 400 kts., have a wingspan of 193 ft., and a height of 20 ft. The aircraft (PA31-350) on path 2 fly at 180 kts., have a wingspan of 44.5 ft., and a height of 10 ft. Given that both paths have one aircraft per hour, the expected number of blind flying collisions was computed to be $N = 0.00041$ per hour.

The collision risk is proportional to the product of the traffic volumes. Assume that the volumes tend to be dependent with an empirical distribution given below:

Frequency of Occurrence	Aircraft per Hour		Blind Flying Collisions /hr
	Path 1	Path 2	
0.2	0.5	0.3	0.00006
0.2	0.5	0.9	0.00018
0.2	1.0	1.0	0.00041
0.3	1.0	1.2	0.00049
0.1	3.0	2.0	0.00243
Weighted Avg.	1.0	1.0	0.00052

The weighted average number of blind flying collisions would be 0.00052 per hour, rather than the 0.00041 based on the average traffic density.

Theoretical Distributions

The above are examples of the use of discrete, empirical probability distributions. A number of models have been constructed using theoretical distributions. Some of the most

popular distributions are the Normal (or Gaussian), the negative exponential, and the Poisson. The first is continuous, symmetrical, and has infinite tails. The second is continuous, produces non-negative values, and has an infinite tail. The third is a discrete distribution with positive probability values at non-negative integers and with an infinite tail.

One of the advantages of theoretical distributions is that they can be manipulated analytically. Another is that an assumed distribution and a few parameters estimated from empirical data can produce probabilities for an infinite number of values, whereas an empirical distribution is limited to the discrete values that have been observed. This is also a disadvantage, especially in the all important issues of the tails. It is typical that collision risk is heavily influenced by the values that are far out on the tails.

Even if the empirical data fit a theoretical distribution very well near the mode, it is by no means certain that the distribution's tails are an appropriate representation. For example, assume that flight deviation from an assigned altitude of 35,000 feet seems to fit a Normal distribution very well with a set of observations that show deviations up to 500 feet above and below the assigned altitude. Use of the Normal distribution would result in a certain probability that the aircraft could be at 60,000 feet or more above or below 35,000 feet. The usual way out of this is to truncate the distribution, with the truncation occurring at some points above and below which the values are deemed unrealistic. The Reich Model [R5.1, R5.2], for example, uses truncation points. But how should these truncation points be determined?

Another problem is that variations in the observed data might be due to a number of different, unrelated causes. For example, altitude deviations of a few hundred feet might be due to sudden changes in wind speed or barometric pressure; deviations of a few thousand feet might be due to miscommunication of assigned altitude; and greater deviations might be due to serious pilot or aircraft problems. Each has its own probability of occurrence and characteristics. The common practice of assuming a single theoretical distribution to cover all might (or might not) be an over simplification. A similar problem arises in modeling horizontal deviations from nominal routes. The same problem can occur in discrete distributions.

One way of dealing with this situation is to derive a "mixture distribution" which is obtained as a weighted sum of the probability density functions of two or more distributions. A theoretically-based model with horizontal track deviations based on the weighted sum of two different Normal distributions (one for navigational errors and one for blunders) is presented in [R5.18; pg. 33].

A bounded, discrete distribution can be based either on values from a truncated theoretical distribution or from empirical measurements. An empirical distribution has finite tails, which are arbitrary, for a few more samples might reveal an even more extreme point. One advantage of an empirical distribution is that it reflects the observed, real world, including gaps, lack of symmetry, multi-modality, etc., that may implicitly represent many

unknown factors. Some apparent quirks might have causes that should be considered explicitly.

In closing, we note that Monte Carlo simulation models, may employ sampling from empirical or theoretical distributions.

5.3.4   Intervention Considerations

The Intersection Model described above produces an estimate of collision risk at the single intersection point of two flight paths. An airspace region contains numerous path intersections, which modeling tools, such as SDAT, can use to estimate collision risk, controller workload, and other metrics. For example, a study conducted using SDAT on sample data from three different ARTCCs, suggested that the blind-flying collision risk amounted to approximately one midair collision per month in the airspace controlled by each ARTCC.

Fortunately, aircraft do not "fly blind." Flight crews are often able (through visual sighting or TCAS alerts) to detect a pending conflict and take appropriate corrective action. In the positive control environment, air traffic control provides separation for all air traffic. The first line of defense is the ATC system, backed up by the flight crews. It is always possible, although extremely rare, that a conflict will proceed undetected until it is too late to perform a maneuver to prevent it. Operational error and pilot deviation reports document cases of this.

In order for a collision to occur, the conditions that would lead to a blind flying collision are required along with a situation in which neither the ATC system nor the flight crews detect and correct the threat in time to prevent it. If the conditions that would lead to a blind flying collision are present, it takes a series of events, each requiring an uncertain, i.e., stochastic, amount of time, to avoid the collision:

> Either:
>
> 1. The controller detects the threat first;
>
>> and
>>
>>> a. The controller orders the first aircraft to maneuver, and
>>> b. The pilot of the first aircraft interprets the controller's communication and moves the aircraft controls, and
>>> c. The first aircraft responds to the controls in time to avoid the collision;
>>
>> and/or
>>
>>> d. The controller orders the second aircraft to maneuver, and
>>> e. The pilot of the second aircraft interprets the controller's command and moves the aircraft controls, and
>>> f. The second aircraft responds to the controls in time to avoid the collision;

or

2. The pilot of the first aircraft detects the threat prior to ATC notification, and
   a. The pilot of the first aircraft moves the aircraft controls, and
   b. The first aircraft responds to the controls in time to avoid the collision;

or

3. The pilot of the second aircraft detects the threat prior to ATC notification, and
   a. The pilot of the second aircraft moves the aircraft controls, and
   b. The second aircraft responds to the controls in time to prevent the collision;

or

4. The aircraft collide.

The above logic does not include every possible combination of events and ignores the relatively remote possibility that both aircraft execute avoidance maneuvers which result in a collision. Note that the question is not whether or not an avoidance maneuver is executed, but whether it is executed in time. This time is the sum of times required for each event in one or another of the processes. If a process is not executed at all, this can be represented by the time being excessive.

The times required for events 1c and 2b are the same, and the times required for events 1f and 3b are the same. But the times for events 1c and 1f could be different if, for example, the aircraft are of different types. The times required for events 1b and 1e could be different, if, for example, the pilots' skills and/or the types of aircraft are different.

The time required for a particular event could be represented by a discrete distribution (perhaps obtained through experiments) in seconds from some given starting point. Event 1a might be measured from the time that the aircraft begin heading on a collision course, perhaps due to a blunder or belated detection of a pending conflict. It includes the time required to decide on an avoidance strategy and to establish communication with the aircraft. It depends on the number of aircraft being controlled, and other controller workload factors. Events 1b and 1d should be measured from the time that event 1a is completed (the controller completes communication with the first aircraft). The time required for event 1c should be measured from the time that event 1b is completed, etc.

The distribution of the total time required to complete a series of events, each of which begins when the previous event ends, can be obtained by a series of convolutions of the (assumed to be independent) distributions. These series of event time convolutions are computed, for example, in the Analytic Blunder Risk Model (ABRM) [see Chapter 6].

5.3.5   Analysis of Separation Standards

Following the above discussion on intervention considerations, the probability of a collision can be approximated by:

$$Pc = P_{cc} \times P_{bf} \times (1-P_1) \times (1-P_2)$$

where:

P_{cc} is the probability that two aircraft are on conflicting, crossing courses, and

P_{bf} is the probability that two aircraft that are on conflicting, crossing courses will arrive at the crossing point close enough in time to result in a collision, assuming that no intervention occurs.

P_1 is the probability that aircraft 1 modifies its course in time to avoid a collision, and

P_2 is the probability that aircraft 2 modifies its course in time to avoid a collision.

$P_1 = Pp_1 + Pa_1 - (Pa_1 \times Pp_1)$, where

Pp_1 is the probability of pilot detection and intervention in time, and
Pa_1 is the probability of ATC-induced intervention in time, etc.

Suppose that two aircraft are separated by exactly the required amount when a blunder occurs. A reduction in separation criteria can affect the individual probabilities resulting from a blunder, as follows:

1. P_{cc} could be increased or decreased, as a blunder in a particular direction (in the horizontal plane, the vertical plane, or both) would be more or less likely to put the aircraft on conflicting courses.

2. P_{bf} could be increased, as the aircraft might be more likely to arrive at the conflict point at the same time.

3. P_1 and/or P_2 could be reduced, as there would be less time for the pilots and controller (it is assumed that both aircraft would be controlled by the same sector) to intervene. There would also theoretically be less time for airframe reaction and a more severe avoidance maneuver might be required.

One computer model for making these computations is the Analytical Blunder Risk Model, described in Chapter 6 of this paper. The weighted average change in collision risk over a family of representative scenarios would approximate the relative change in risk due to a blunder under a postulated decrease in separation standards. How one would construct these scenarios and changes in probabilities is a serious challenge.

5.4 FAST-TIME (MONTE CARLO) AND REAL-TIME SIMULATION MODELS

A real-time simulation is a carefully controlled experiment combining the power and graphical display capabilities of today's computers with the knowledge and skill of human subjects, such as pilots and air traffic controllers, to operate equipment, either simulated or real, such as aircraft and radar facilities. Since time cannot be compressed because of the human participants, the simulations are referred to as real-time simulations. A real-time simulation is typically an extremely complex endeavor involving several participants, (e.g., controllers, engineers, analysts, and ergonomists) requiring elaborate facilities for its performance, and possibly requiring a year or longer to complete.

Real-time simulations of aircraft and air traffic control operations have been used increasingly by the FAA and EUROCONTROL in the evaluation of new procedures and airport configurations. In real-time simulations, controller and aircrew/aircraft performance can be measured individually and combined in the system performance measures. One benefit of conducting real-time simulations with human operators is that unexpected effects of the procedure on system performance can be identified. A limitation of real-time simulations is that only a relatively small number of conditions can be tested economically. Thus, the data collected is usually a very small subset of all the possible conditions.

Real-time simulations are used to provide the Air Traffic Management (ATM) community the most accurate information possible on the impact of change and new developments in its ATM facilities and procedures. They provide the capability to study modifications in airspace sectorization, aircraft routing, control procedures, the state-of-the-art in controller interfaces and new tools. One can assess the effects of delays, fuel expenditure, safety aspects of new procedures, and controller workload. To run a real-time simulation, the client provides the controllers (typically 20-25). The simulation facility provides a representation of the normal or proposed ATC environment. The controllers come to the FAA or EEC (Eurocontrol Experimental Centre) facilities for an agreed period arranged to address the objectives of the simulation. During this time, data and a variety of measures are collected to allow the client to obtain objective and subjective assessments of the environment being studied. On the basis of the researchers knowledge and past experience, recommendations based on the results may also be offered.

The value of real-time simulation data must be weighed against the "simulation effect." Simulation, by definition, is not "the real thing." This effect is visible as controllers doing things they would not do in the normal practice of ATC and considerably higher simulated traffic levels being considered "acceptable" than would be the case in reality. This can be seen as desirable or undesirable. In some cases, it is also evident that participants tolerate poor interaction with the simulated system because it is a simulation.

The purpose of a real-time simulation is to produce estimates of parameters that are used in the decision process. Because of the small set of data collected in real-time simulations, there is the possibility of a relatively large margin of error in the observed decision parameters. Only a relatively small number of combinations of human factors, such as pilot and controller reaction times, and aircraft dynamic parameters have been used to produce the estimate of the decision parameters. Therefore, confidence intervals are typically established to estimate the range of the decision parameters. Since the sample sizes are relatively small, the confidence intervals are correspondingly large. It is possible that a decision to accept or reject a procedure could be in error because of the size of the confidence interval used to estimate the decision parameter. In addition, because of economic or time considerations, it may have been necessary to omit some possible configurations of interest from the real-time simulation.

One way to refine and/or expand the results of a real-time simulation is to conduct a fast-time computer simulation, commonly called a Monte Carlo simulation. This technique has been used successfully in several FAA programs such as the Multiple Parallel Approach Program (MPAP), the Precision Runway Monitor (PRM) Demonstration Program, and by the Converging Approach Standards Technical Work Group (CASTWG) to assess the probability of midair collisions during simultaneous parallel or converging approach operations. This approach is discussed more fully in Section 5.4.3.

A fast-time simulation uses the actual aircrew/aircraft and air traffic controller performance data collected in the real-time simulation and can examine over 100,000 aircraft operations or phenomena such as blunders in a short period of time. This large number of observations results in very small confidence intervals for the decision parameters, based on the input real-time data.

The fast-time model used by the MPAP and CASTWG is the Airspace Simulation and Analysis for TERPS (ASAT) System, where TERPS stands for Terminal Instrument Procedures. This model was developed by the FAA's Standards Development Branch, AFS-450, as an analysis tool for the evaluation of controller, aircrew/aircraft, and system performance.

5.4.1 Real-Time Simulation Modeling

Up until the end of 1995, real-time simulations in Europe were the responsibility of the Eurocontrol Experimental Centre (EEC) Division B1.1. With the reorganization of the Experimental Centre in January 1996, the Real-Time Simulation Operations (RTO) Centre of Expertise came into being.

RTO is responsible for the day-to-day management of the real-time simulation program carried out at the Centre. It is involved in all stages of a simulation - from the Simulation Request to the publication of the Final report. Its purpose is to coordinate with the Client and with the other Centres of Expertise to ensure that the simulation runs smoothly from start to finish. It also provides operational expertise to other Centres of Expertise.

Real-time simulation is also an important research tool in the United States. For example, the MPAP real-time simulations that were performed at the FAA Technical Center in Atlantic City, New Jersey were designed to test the ability of pilots and controllers to safely resolve blunders that may occur during simultaneous parallel instrument approach operations. Because of the expense and time required to perform a real-time simulation, a real-time simulation is best suited for the study of maneuvers of short duration, such as missed approaches, or anomalous events, such as blunders.

A typical, real-time simulation requires a system consisting of three types of components: the Target Generation Facility (TGF) laboratory, the radar system and controller displays, and flight simulators. The following paragraphs describe one such system.

Target Generation Facility

The FAA's TGF is an advanced simulation system that is partitioned into three subsystems: simulation pilot work stations, target generation, and development and support. The target generation subsystem is a computer system that generates target aircraft to display on the controller radar screens. The target aircraft are used to provide a realistic traffic flow and are operated from computer keyboards by Simulation Pilot Operators (SPO). The SPOs are not required to be pilots; however, they must be trained in radio phraseology and the operation of the specialized keyboards which control the simulated radar targets.

The TGF also performs modeling of weather vectors and radar performance. The TGF receives input from the flight simulators and displays the position of the flight simulations on the controller radar screens. The TGF processes and records the flight tracks generated during the simulation. The TGF is the central operating system of the simulation.

Radar System and Controllers

Prototypes of the Precision Radar Monitor (PRM) system provide high precision secondary surveillance data to Final Monitor Aid (FMA) radar display consoles located in the Systems Display Laboratory at the FAA Technical Center. The FMAs are high resolution color displays equipped with a controller alert system used in the simulated PRM system. The Systems Display Laboratory is also equipped to simulate several other types of radar such as ASR-9 and E-Scan, as well as other types of monitor displays such as FDADS (Fully Digital Alphanumeric Display System) and DEDS (Digital Entry Display System). In a typical simulation, sixteen experienced air traffic controllers participate as test subjects. The controllers are selected from various TRACON facilities across the United States. Controllers are scheduled to participate in groups of four, with two groups participating each week of the test.

Flight Simulators and Pilots

Flight simulators with airline pilots at the controls are used for evading aircraft during simulated blunders. Flight simulators assume the configuration of aircraft flying the localizer course and replace TGF aircraft that are scheduled to enter the simulation. Approach type (i.e., coupled autopilot, flight director, or raw data) are scripted for the flight simulators based upon surveys of current airline procedures. Flight simulators and airline pilots are essential to obtain valid data of pilot and aircraft performance during a blunder maneuver.

Evaluation of Simulation Results

Before the simulation begins, it is essential that all test parameters that will be used in the evaluation of the simulation have been determined and that criteria have been established to determine the acceptability of the operation being tested. In the case of the MPAP simulations, the primary concern is to estimate the risk of collision during parallel approach operations. It was decided that a center-of-gravity to center-of-gravity distance between two aircraft of less than 500 feet would be unacceptable and called a Test Criterion Violation (TCV). Other factors used in the evaluation include communications workload, the number of nuisance breakouts (NBO), and an operational evaluation by test observers.

The most important element in the evaluation process is the TCV. Although a TCV does not necessarily result in a collision, for simplicity, a TCV is regarded as a collision. The analysis of the data focuses on the TCV rate. Before a TCV can occur, even without controller intervention, the two aircraft must be located at appropriate positions relative to the runway threshold, which is based on the aircraft speeds and the angle the blunder forms with the extended runway centerline. An interval can be determined mathematically so that if the evading aircraft is within this interval when the blunder begins and no evasion action is taken, a TCV will occur. This interval is called the window of risk. Because the window of risk is short and the number of simulated blunders is small, a simulation could easily result in zero TCVs if the simulated aircraft are situated at random on the approach path. This could lead to an erroneous acceptance of an unsafe operation. Therefore, simulated aircraft are purposely aligned so that the simulated blunder will result in a TCV without timely controller and pilot action. When the evading aircraft is situated in the window of risk, it is said to be at-risk.

The probability of a collision can be estimated from the rate of TCVs per at-risk blunder. Because of the small number of at-risk blunders generated during the real-time simulation, the estimate of the TCV rate is subject to random fluctuations. An upper confidence limit is used to find a "worst case" or conservative value for the TCV rate. If this value is less than the predetermined acceptable TCV rate, the operation can be accepted as safe. If the raw or observed TCV rate is larger than the acceptable TCV rate, the operation can be rejected. However, if the acceptable TCV rate is between the upper confidence limit and the observed TCV rate, it is unclear whether the operation should be accepted or rejected.

The fast-time simulation is employed to shorten the confidence interval of the TCV rate resulting in a more accurate estimate of the actual TCV rate.

5.4.2   Fast-time (Monte Carlo) Simulation Models

The purpose of a fast-time simulation is to provide a more accurate estimate of the acceptance parameter than the estimate derived from the real-time simulation. In the real-time simulation, because of budgetary and time considerations, only a small number of simulated operations can be performed. This means that combinations of controller response times, pilot response times, and other human factor related parameters have not been fully explored. Other factors that are not fully explored are related to weather phenomena such as wind speed and direction and aircraft parameters related to the size and speed of the aircraft performing the operation. Because of the large number of combinations left unexplored in the real-time simulation, the actual value of the acceptance parameter may be different than that observed in the real-time simulation.

A fast-time simulation must be carefully constructed in order to instill confidence in the estimate of the acceptance parameter. Because of the unique characteristics of aircraft trajectories, the fast-time simulation model should employ flight dynamics representing aircraft currently used in commercial operations. The model should employ advanced statistical techniques to model human factors data captured during the real-time simulation. A simulation system that incorporates these features is the FAA's Airspace Simulation and Analysis for TERPS (ASAT) system.

5.4.3 Fast-Time Simulations Using the Airspace Simulation and Analysis for TERPS (ASAT) Computer System

The Airspace Simulation and Analysis for TERPS (ASAT) system has been developed by the FAA Standards Development Branch, AFS-450, to perform complex multiple aircraft simulations in order to study the obstacle clearance and airspace requirements for new standards such as multiple parallel approaches and GPS/WAAS routes, as well as re-evaluation of existing standards such as those for holding patterns.

Composition of the ASAT Computer System

The ASAT system combines high fidelity flight dynamics and FMS/autopilot models with realistic atmospheric models for wind, temperature and pressure; models of surveillance systems such as E-scan and ASR-9 radar, human factors such as pilot and ATC responses, and delays and tolerances to produce realistic simulations of flight operations. The flight dynamics and FMS/autopilot models were developed from flight data supplied by aircraft manufacturers and are comparable in fidelity to the flight dynamics models used in certified motion-based flight simulators. The atmospheric model is also comparable to those used in certified motion-based flight simulators. In the ASAT computer system, all aircraft can be simulated using realistic flight dynamics models.

For simulations such as multiple parallel approaches, aircraft are positioned on the glide slope using lateral and vertical distributions of error from the ICAO Collision Risk Model (CRM). The CRM is used internationally to compute the probability of collision with ground-based obstacles during an Instrument Landing System (ILS) approach. The probability distributions used in the CRM were developed from actual flight data and have been periodically validated by AFS-450 by comparison to the most recent flight data available. The probability distributions permit the simulation of hand flown, flight director, and autopilot approaches. The CRM is maintained by AFS-450 for application in the United States.

The fast-time component of ASAT combines probability distributions of pilot response times, ATC reaction times, radar errors, aircraft roll rates, climb rates, airspeeds, and maximum bank angles to produce accurate flight tracks of aircraft. All distributions, except radar error, are derived from data collected during the real-time simulation. Statistical methods are used to determine mathematical curves (i.e., theoretical probability distributions) that statistically fit the empirical data collected from the real-time simulation. For example, ATC response times collected during the real-time simulation form an empirical distribution. This empirical distribution will have numerous gaps since the distribution was formed from a relatively small data base. Often in these types of data, large gaps will appear between the largest and the next largest observed times. In addition, the appearance of a long response time indicates that longer response times are possible. If the fast-time simulation were to use the empirical distribution for sampling purposes, there would be time intervals which would never be represented in the simulation and no possibility of a response time larger than those observed. By fitting a statistically valid, continuous curve to the empirical data all gaps are filled and a small probability exists that a time larger than the largest observed time may be chosen during the fast-time simulation.

Another feature of the ASAT system is the ability to perform sensitivity analysis. The term, sensitivity analysis, refers to the variation of certain parameters by the experimenter to determine the effect on the results of the simulation. Since parameters derived from sample data are imprecise estimates of reality, the experimenter makes small changes to determine the range of possible results. For example, if the reaction times observed during the real-time simulation are thought to be, on average, too short, then the mean of the mathematical probability distribution may be increased. In this fashion, the maximum average reaction time that will result in the simulation meeting the target level of safety may be determined. Since the ASAT model uses distributions of observed aircraft performance, such as maximum bank angle, the aircraft performance parameters may also be subjected to sensitivity analysis.

Operation of the ASAT Computer System

The operation of the ASAT system will depend on the operation being simulated. The purpose of the simulations is to estimate the probability of a TCV as a result of one aircraft turning unexpectedly from an ILS localizer or en route track toward another

aircraft on an adjacent ILS approach or en route track. The simulated blunder is assumed to be the result of a problem that the crew is unable to resolve regardless of instructions from air traffic control (ATC). The blundering aircraft is assumed to turn to a heading 30 degrees from the heading of the aircraft prior to the blunder. This type of blunder is called a worst-case blunder. The aircraft on the parallel approach, called the evader, is assumed to continue the ILS approach until contacted by ATC.

Before the simulation of the blunder can begin, the two aircraft must be placed on their respective ILS approaches. The range of the blundering aircraft from threshold is first determined. The range can be chosen randomly in a predetermined interval or it can be set to a desired constant such as 3 nm. Then the lateral and vertical deviations of the blundering aircraft from the glide path are chosen at random from the CRM distributions. The CRM distributions have thicker tails than a Normal distribution and have standard deviations that grow larger as the range grows larger. The speed of the blundering aircraft is also chosen randomly at this time.

The lateral and vertical position of the evading aircraft, as well as its speed, are then chosen at random. Then the range of the evading aircraft is chosen. The range may be chosen at random, or the range may be chosen so that the simulated blunder is at-risk.

The blunder is initiated by rolling the blundering aircraft into a standard rate of turn toward the evading aircraft. Since actual flight dynamics are used in the ASAT fast-time simulation, the flight path will differ from the flight paths of the blundering aircraft in the real-time simulation. Pilot reaction time is measured in the real-time simulation from the time that the controller is alerted by the PRM that the blundering aircraft will enter the Non-Transgression Zone (NTZ) in ten seconds. Radar error is applied to the positions of the two aircraft during the maneuver to produce a random effect on the NTZ alert time.

ATC response time is chosen randomly from its distribution and added to the NTZ alert time to determine the time ATC begins its transmission to the evading aircraft. Pilot response time is randomly selected from its distribution and added to the cumulative time to find the time at which the pilot begins his or her evasion maneuver. Then the distributions of roll rate, rate of climb, maximum bank angle, and heading change are used to find random values for the evasion maneuver.

The slant distance between the two aircraft is computed twenty times per simulated second from the start of the blunder. The blunder is stopped when it is determined that the Closest Point of Approach (CPA) has occurred. The value of the CPA is added to the set of CPA data and if a TCV occurred it is also added to the file of TCV data. The model then begins the process again by selecting positions of the aircraft for the next blunder.

<u>Simulation Implementation</u>

Before a simulation can begin, the ASAT model must be configured appropriately. For example, in the MPAP simulations, the runways and approaches in the ASAT system are set to match those in the real-time situation. In these simulations, the distance between runways is set and runway threshold stagger is also set. Offset approaches can also be modeled. Other parameters that are adjusted prior to simulation are field elevation, altimeter setting, wind velocity, and glide slope angle. Parameters such as visibility, and ceiling are not pertinent to the Monte Carlo simulation.

Empirical distributions of ATC response times and pilot response times are obtained from the real-time simulation performed at the FAA Technical Center. Similarly, empirical distributions of aircraft performance data, indicated airspeeds, roll rates, maximum bank angles, and rates of climb are derived from data acquired during a real-time simulation. Special software tools have been developed by ASF-450 for the efficient collection of aircraft data from the flight track data recorded during the real-time simulation. Since several different aircraft simulators are used in the real-time simulation, differences in aircraft characteristics such as roll rates, indicated airspeeds, and rates of climb are expected. The empirical data is statistically tested for similarities and the data is pooled into larger sets whenever possible. Mathematical probability curves are fit to the empirical distributions using statistical methods. The empirical data sets generated by the real-time simulation are not from Normal or other standard distributions, so special techniques are required to fit curves to the data.

5.4.4 Evaluation of Simulation Results

The evaluation of the simulation results is just as important as the simulation itself. The evaluation method should be developed as an integral part of the simulation. The data output of the simulation should be designed specifically for the evaluation which will be employed. The acceptance criteria should be defined before the simulation begins. For example, in the MPAP the evaluation of the operation depends primarily on the TCV. The TCV represents the possible collision of two aircraft. It is necessary to estimate the probability of a TCV and then to determine an acceptable upper limit for that probability.

For example, several events must occur simultaneously for a collision to occur during simultaneous instrument approaches. Clearly, a blunder must occur, or there would be no significant deviation from course. Previous testing has shown that blunders less than Worst Case (a blunder with a 30° heading change) are of negligible risk, so the blunder must be a Worst Case Blunder (WCB). Also, the blundering aircraft must have a critical alignment with an aircraft on an adjacent course, that is, it must be at-risk. If all of the above events develop, a TCV will occur if the air traffic controller and the pilots cannot react in sufficient time to separate the blundering and the evading aircraft. Since the preponderance of fatal accidents involve only one aircraft, accident rates are based on single aircraft accidents. Therefore, for comparison purposes, since one collision will involve two aircraft it will be considered to produce two accidents. Assuming that a TCV

will result in a collision, the probability of a collision accident can be expressed in mathematical terms by:

(1)   P(Accident) = P(TCV and At-risk and WCB and Blunder) x 2

or

(2)   P(Accident) = P(TCV|At-risk and WCB and Blunder)
                             x P(At-risk|WCB and Blunder)
                             x P(WCB|Blunder)
                             x P(Blunder) x 2 ,

   where:

   P(TCV and At-risk and WCB and Blunder) is the probability of all relevant events occurring simultaneously, that is, an at-risk WCB that results in a TCV.

   P(TCV|At-risk and WCB and Blunder) is the probability that a TCV occurs given that an at-risk WCB has occurred. This quantity is estimated by the simulation of at-risk WCB in the real-time and Monte Carlo simulations (i.e., the TCV rate in the simulation).

   P(At-risk|WCB and Blunder) is the probability that a WCB has critical alignment with an aircraft on an adjacent approach.

   P(WCB|Blunder) is the probability that a blunder is a WCB.

   P(Blunder) is the probability that a blunder occurs during a simultaneous instrument approach.

   The factor of 2 represents two accidents per collision.

Ideally, the probability of an accident occurring during the tested approach operation could be computed from Equation (2) and a determination made of its acceptability. An acceptability criterion can be based on a Target Level of Safety.

5.4.5 Obtaining a Maximum Allowable TCV Rate Based on a Target Level of Safety

Determining a Target Level of Safety

An example of the determination of a Target Level of Safety (TLS) is a method applicable to parallel approach operations. This method can adapted to en route operations.

The total number of air carrier accidents, as well as the number of fatal accidents on final approach, has been extracted from National Transportation Safety Board (NTSB) data for

the time period, 1983-1989. This number, together with the total number of ILS approaches flown during this time period, leads to an estimated fatal accident rate of 4 x 10^{-7} fatal accidents (ACC) per ILS approach (APP) during IMC. There are a number of causes of accidents during final approach, such as structural failure, engine failure, or midair collision. An initial estimate is that there are nine possible causes of accidents on final approach. A tenth possible accident cause, a collision with an aircraft on an adjacent approach, is created with the implementation of simultaneous parallel approaches.

For simplicity of model development, it is assumed that the risks of the ten potential accident causes are equal. Thus, the contribution of any one of the accident causes would be one-tenth of the total accident rate. Based on this, the target safety level for midair collisions on simultaneous parallel approaches is 4 x 10^{-8}, or

$$\frac{1 \text{ ACC}}{25 \text{ mill APP}}$$

Determining a Maximum Allowable TCV Rate

Since the only undefined variable in equation (2) [Section 5.4.4, pg. 26] used to compute the maximum acceptable blunder rate, is the TCV rate, it is possible to determine the maximum allowable TCV rate which would meet the target level of safety. Knowledge of this number would permit a quick decision regarding the acceptability of the simulated operation. The maximum allowable TCV rate may be found from the following analysis.

Given the target level of safety, P(Accident) = 4 x 10^{-8}, then from equation (2) one has

P(TCV|At-risk and WCB and Blunder) x P(At-risk|WCB and Blunder)
    x P(WCB|Blunder) x P(Blunder) x 2 = 4 x 10^{-8} ,

or

(3)   P(TCV|At-risk and WCB and Blunder)

$$= \frac{4 \times 10^{-8}}{1} \quad \text{x} \quad \frac{1}{\text{P(At-risk|WCB and Blunder)}} \quad \text{x} \quad \frac{1}{\text{P (WCB|Blunder)}}$$

$$\text{x} \quad \frac{1}{\text{P(Blunder)}} \quad \text{x} \quad \frac{1}{2}$$

Values from equation (2) can be substituted into equation (3) to obtain a maximum acceptable TCV rate. After completion of the simulation, the acceptability of the simulated operation can be easily determined.

It should be remarked that no matter how small a target level of safety is chosen for a new operation, procedure, etc., the overall level of risk will increase unless the new operation has the effect of reducing the risk of one or more current operations.

5.4.6   Summary

A real-time simulation uses human subjects such as pilots and air traffic controllers to operate equipment, either simulated or real, such as aircraft and radar facilities. A real-time simulation is typically an extremely complex and costly endeavor, but it provides insight into possible operational problems and it provides human factors and aircraft performance data. Acceptance criteria based solely on a real-time simulation may be difficult to apply because of the small size of the sample provided by the simulation.

The purpose of a fast-time (Monte Carlo) simulation is to provide a more accurate estimate of the acceptance parameter than the estimate derived from the real-time simulation. Data derived from the real-time simulation are used to develop probability distributions of human factors and aircraft performance. These probability distributions are used in a fast-time simulation to explore the probability of events which would not likely be covered by the real-time simulation. In addition, the large sample sizes attainable in a fast-time simulation will result in a more precise estimate of the acceptance parameter.

5.5   HUMAN FACTORS IN ATM SAFETY MODELING: THE VARIABILITY IN HUMAN ACTIONS

When assessing safety in present or future ATM environments, a key role is played by human operators (air traffic controllers and pilots). This is because safety critical tasks, like solving conflicts between aircraft, involve a lot of human activity, from conflict detection to maneuvering the aircraft to a different flight-level.

Due to the presence of human operators in the ATM environment, the behavior of the ATM environment cannot be looked upon as a deterministic process. Where machines in general take one course of action, humans can (and will) select a solution to the current problem from a range of possibilities, where the specific choice of action also depends on subjective parameters as workload, subjectively available time, and operator level of performance. Thus, the presence of human operators causes a variety of possibilities for the evolution of the traffic flow.

If we relate this to safety, we argue that we cannot speak of a 'human error' when an unsafe situation originates from certain actions of the human operator. Regarding these operator actions as 'erroneous' does not pay proper respect to, for example, situations where the operator (e.g., an air traffic controller) chooses to let an even more urgent problem receive attention when the subjectively available time is short or when high workload (e.g., many conflicts to be resolved) causes one to make quick decisions, without bothering too much about the quality of those decisions. Note that these effects

are inextricably bound up with human flexibility and the ability of humans to deal with unforeseen situations.

When assessing ATM safety, it is necessary to take these aspects of human performance into account. For this purpose, NLR has developed a high-level model of human performance that has been implemented into TOPAZ (Traffic Organization and Perturbation AnalyZer) that can be adjusted to the specific ATM situation under consideration. The model has been developed in cooperation with NLR's Human Factors Department and is based upon the cognitive model of the well-known human factors specialist Erik Hollnagel [R5.20].

The results of the NLR contribution to the RHEA project (Role of the Human in the Evolution of ATM) [R5.21] show that this fast-time human performance modeling approach is feasible when evaluating ATM conceptual developments with respect to safety.

List of References

R5.1 Reich, Peter G., "Analysis of Long-Range Air Traffic Systems: Separation Standards--I, II, and III," <u>The Journal of (the Institute of) Navigation</u>, Vol.19 (1966), No. 1, pp. 88-96; No. 2, pp. 169-176; No. 3, pp. 331-338. [Note: Contains same material as R5.2.]

R5.2 Reich, Peter G., "A Theory of Safe Separation Standards for Air Traffic Control," Farnborough, United Kingdom: Royal Aircraft Establishment, RAE Technical Reports Nos. 64041, 64042, 64043, 1964. [Note: Contains same material as R5.1.]

R5.3 Machol, R., "Thirty Years of Modeling Midair Collisions," <u>Interfaces</u>, Vol.25 (1995), No 5, pp.151-172.

R5.4 Simpson, Robert W., and Raymond A. Austrotas, "Modelling Risk in ATC Operations with Ground Interventions," MIT Flight Transportation Laboratory Report R 91-6, July 1991.

R5.5 Davies, Liz and Andrew Sharpe, "Review of the North Atlantic Lateral Collision Risk Model," <u>Air Traffic Control Quarterly</u>, Vol. 1, No. 3, 1993.

R5.6 ICAO RGCSP/9-WP/25, Manual on Airspace Planning Methodology for the Determination of Separation Minima, Version 3.0, 26 Feb. 1996.

R5.7 RTCA, "Terms of Reference, Air Traffic Services Safety and Interoperability Requirements," RTCA SC-189/EUROCAE WG 53.

R5.8 Joseph, Mark, "Air Traffic Services Safety and Interoperability Requirements Position Paper," MITRE CAASD & RTCA SC-189/EUROCAE WG-53, 6 June 1997.

R5.9 Everdij, M., M. Klompstra, H. Blom, and O.N. Fota, "Final Report on Safety Model, Part I: Evaluation of Hazard Analysis Techniques for En route ATM," MUFTIS Work Package Report 3.2, The Netherlands: National Aerospace Laboratory, NLR Technical Report No TR 96196L, 1996.

R5.10 Everdij, M., M. Klompstra, and H. Blom, "Final Report on Safety Model, Part II: Development of Mathematical Techniques for ATM Safety Analysis," *MUFTIS Work Package Report 3.2*, The Netherlands: National Aerospace Laboratory, NLR Technical Report No TR 96197L, 1996.

R5.11 Fota, O.N., "Etude de Faisabilitité d'Analyse Globale de la Sécurité d'un CCR à l'aide de l'EPS (Evaluation Probabiliste de la Sécurité)," Centre d'Études de la Navigation Aérienne, Rapport CENA/R93-022, 1993.

R5.12 "Hazard Analysis of an En route Sector, Volume 1 (main report)," Civil Aviation Authority, RMC Report R93-81(S), 1993.

R5.13 "Hazard Analysis of an En route Sector, Volume 2," Civil Aviation Authority, RMC Report R93-81(S), 1993.

R5.14 Foot, P.B., "A Review of the Results of a Trial Hazard Analysis of Airspace Sectors 24 and 26S," Civil Aviation Authority, CS Report 9427, 1994.

R5.15 Smith, E.J., "Hazard Analysis of Route Separation Standards for EUROCONTROL," *DNV Technica*, 1994.

R5.16 Shepherd, Roger, Rick Cassell, Rajeev Thapa, and Derrick Lee, "A Reduced Aircraft Separation Risk Assessment Model," *Proceedings of the AIAA Guidance, Navigation, and Control Conference, New Orleans, August 10-13, 1997*.

R5.17 Siddiqee, W., "A Mathematical Model for Predicting the Number of Potential Conflict Situations at Intersecting Air Routes," *Transportation Science*, No. 7, (1973).

R5.18 Applied Techno-Management Systems, Inc. (ATMS), "Potential Operational Impacts of GPS with Advanced CNS and ATC Automation Technologies," Falls Church, VA: FAA Contract #DTA01-94-Y-00039, February 9, 1996.

R5.19 Geisinger, Kenneth, "Airspace Conflict Equations," *Transportation Science*, Vol. 19, No. 2, May 1985, pp. 139-153.

R5.20 Hollnagel, E., *Human Reliability Analysis Context and Control*, Academic Press, London, 1993.

R5.21 Biemans, M.C.M., J. Daams, *HOMEROS: Human Operator Modelling to Evaluate Reliability, Organisation and Safety*, RHEA/TH/WPR/6/1, European Union DGVII, Contract number AI-95-SC.107, NLR, 1997.

[This page intentionally blank.]

6.0   EXISTING MODELS AND MODELING TOOLS

6.1   THE ANALYTIC BLUNDER RISK MODEL (ABRM)

Background

The Analytic Blunder Risk Model (ABRM) is an analytic/probabilistic collision risk model programmed in Microsoft EXCEL.[1] The model estimates collision risk for a <u>given single-event scenario</u> consisting of two aircraft under air traffic control: a blunderer (an aircraft deviating from a safe trajectory to one that crosses the path of another aircraft) and an evader (the threatened aircraft). Both aircraft are assumed to fly in a constant direction and at a constant speed during the blunder, unless an evasion maneuver is executed. The evasion, if completed in time, is assumed to be successful. (The possibility of an evasion resulting in a collision exists, but is relatively unlikely and can be handled in a separate analysis.)

Definitions

The following definitions are made to facilitate the discussion:

A <u>blunder</u> is an air traffic situation in which two aircraft are on courses which cause, or will cause (unless corrected), a simultaneous violation of minimum separation requirements (in the horizontal plane and the vertical plane), i.e., a <u>conflict</u>. A blunder could be caused by an inappropriate change in direction, speed, and/or climb/descent angle on the part of one of the aircraft (the blunderer), or it could be caused by a pending conflict going undetected beyond the latest time at which corrective action should have been taken. In the later case, this time could be taken to be the moment the blunder occurred.

A <u>collision</u> is the result of a blunder which causes horizontal separation to be less than the average diameter of the two aircraft and vertical separation to be less than the average heights of the two aircraft (considered as discs).

<u>Air traffic control (ATC) reaction (or response) time</u> is the time between when a blunder occurs and the time required for an air traffic controller to observe the threat, decide on a corrective action, obtain a clear radio channel, and convey instructions to the flight crew. It depends on the number of aircraft being monitored by the controller, the skill level of the controller, the scan rate and display capability of the ATC equipment, the nature of the threat, random factors, etc.

<u>Flight crew reaction time</u> is the time required between the moment that instructions are conveyed by the controller and the moment that controls in the cockpit are moved

---

[1] The model was created by Ken Geisinger (ATX-400) with the assistance of several George Washington University students over a number of years.

appropriately. This time depends on the type of aircraft, the skill level of the pilots, the time required to disengage automatic controls (if necessary), the interference of other flight control activities, random factors, etc.

Airframe reaction time is the time required between the moment that controls are adjusted and the moment that the aircraft responds with a suitable change in direction, speed, or rate of climb/descent. This is a function of the type of aircraft; the current trajectory, speed, altitude, throttle setting, atmospheric conditions; and random factors.

Blunder duration is the time between the moment that the blunder occurs and the moment that either aircraft executes an avoidance maneuver without the assistance of ATC (e.g., through visual or Traffic Alert and Collision Avoidance System (TCAS) detection of the threat). Note that by this definition, a blunder can continue to endure indefinitely, but the model is only concerned with whether or not it endures when the blunderer crosses (or would have crossed) the evader's path.

Required Input Data

The following are required input data:

ALPHA1 = Climb (if positive) or descent (if negative) angle of the blunderer (degrees).
ALPHA2 = Climb (if positive) or descent (if negative) angle of the evader (degrees).
PHI = Crossing angle of the blunderer and evader paths in the horizontal plane (degrees).
       Note: it is required that 0 < PHI < 180 degrees.
SPEED1 = Speed of blunderer along the flight path (knots).
SPEED2 = Speed of evader along the flight path (knots).
INSEPH = Initial distance from blunderer to closest point on the evader path in the
       horizontal plane, in nm.
INSEPV = Initial vertical separation between the blunderer and the closest point on the
       evader path in feet (negative if evader path is above blunderer).
HEIGHT1 = Height of blunderer aircraft, in feet.
HEIGHT2 = Height of evader aircraft, in feet.
WSPAN1 = Diameter of blunderer, in feet.
WSPAN2 = Diameter of evader, in feet.
TRFDTY = Number of aircraft per hour on evader path.

Initial distances refer to distances at time zero, which is taken to be the time that the blunder occurs. Seven response time distributions are required, as discussed below.

Methodology

Given that a blunder occurs, the probability of a collision can be approximated by:

$$Pc = (Pn) \times (Pb) \times (Pe) \times (Ps)$$

where,

Pn is the probability that both aircraft will arrive at the crossing point close enough in time and space to result in a collision, assuming that no intervention occurs. Pn is a function of PHI, ALPHA, SPEED, HEIGHT, WSPAN, TRFDNTY, and H, the vertical separation (in feet) between paths at the crossing point, which is computed.

The function Pn is derived in "Airspace Conflict Equations" [R6.1]. This function is a three-dimensional model that assumes that the aircraft fly at constant speed, direction and climb angle through the intersection and that a specified number of evaders per hour are randomly distributed according to the uniform probability distribution on the evader course.

Pb is the probability that ATC intervention will not cause the blunderer to modify its course in time to avoid a collision.

Pe is the probability that ATC intervention will not cause the evader to modify its course in time to avoid a collision.

Ps is the probability that neither modifies its course in time to avoid a collision without ATC intervention.

The probability that an ATC-assisted avoidance maneuver on the part of the blunderer does not occur in time is given by:

$Pb = Prob(Tbe > Tc)$

Where,

Tbe = time required for the blunderer to evade (probability distribution), and

Tc = time (in seconds) between the moment of initiation of the blunder to the moment that the blunderer would cross the evader's path, assuming that no evasion occurs.
The probability that a successful ATC-assisted evader correction does not occur in time is:

$Pe = Prob(Tee > Tc)$

Where,

Tee = time required for the evader to evade (probability distribution).

Both Tbe and Tee are computed through numerical convolution of user-specified probability distributions for the three reaction times described above (air traffic control, flight crew, and airframe).

Ps is given by:

$$Ps = Prob(Tsc > Tc)$$

Tsc is the time, in the absence of ATC intervention, from the initiation of the blunder until either aircraft flight crew detects and reacts to the threat, and their aircraft executes an avoidance maneuver. If both aircraft execute avoidance maneuvers, the shorter reaction time is used. (Future versions of the ABRM will explicitly consider visual detection and TCAS alerts.)

Figure 6-1 is a flow diagram of the basic logic in the ABRM, showing input data and the steps leading to the computation of Pc for a given collision risk scenario. Probably, the best way to illustrate the operation of the ABRM is through a hypothetical example.

Analytic Blunder Risk Model
Simplified Overall Logic

Given trajectories of Blunderer, B and Evader, E	Compute time, Tc from start until B crosses E's path	Given P.D. ATC reaction time for blunderer, Tba	Given P.D. pilot reaction time for blunderer, Pbp
Compute Pb = prob. that Tbe > Tc	Compute P.D. total reaction time for blunderer, Tbe	Given P.D. A/C reaction time for blunderer, Tbf	
Compute Prob. of Blind Flying Collision = Pn	Given P.D. ATC reaction time for evader, Tea	Given P.D. pilot reaction time for evader, Tep	Given P.D. A/C reaction time for evader, Tea
Given P.D. of self correction time for either, Ts	Compute Pe= prob. that Tee > Tc	Compute P.D. total reaction time for evader , Tee	

Compute Ps = Prob. that Ts > Tc

Prob. of Collision PC=Pn*Pb*Pe*Ps

Note: P.D. = probability distribution
ATC = air traffic control
A/C = aircraft
Blunderer = deviating A/C
Evader = potentially threatened A/C

Figure 6-1. Analytic Blunder Risk Model Logic

Hypothetical example

As a hypothetical example, consider the following problem which is based on an actual operational error in which an aircraft was vectored and cleared to descend in the face of oncoming traffic 2,000 feet below:

Aircraft data:	Evader	Blunderer
Wingspan	125	108 feet
Height	40	30 feet
Speed	502	398 knots
Climb angle	0	-4 degrees

Blunder data
Crossing angle (PHI)   =   120 degrees
Initial separation   INSEPH = 4 nm ,   INSEPV = 2000 feet
Evader traffic density (TRFDTY) = 1 aircraft/hour

A set of hypothetical reaction time distributions were used to obtain the overall reaction time distributions for controller intervention and self-correction. The result for controller intervention to correct the blunderer is shown in Figure 6-2, where both the probability density and cumulative probability distribution functions are displayed. In this example, the minimum possible reaction time is 26 seconds, and there is about a 10 percent chance that the correction won't happen at all (possibly due to controller not observing the threat, blocked radio frequency, non-responding flight crew, etc.)
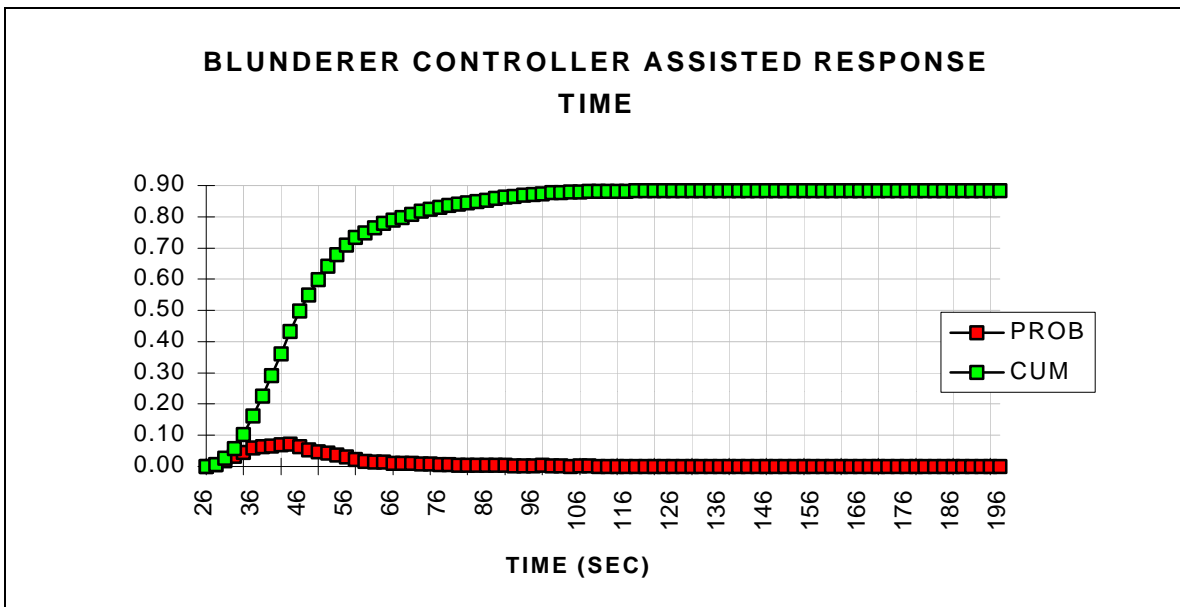
Figure 6-2. Example of an ABRM Response Time Distribution (Hypothetical Data)

The results obtained are:

Horizontal separation requirement (R)   = 116.5 feet
Vertical separation requirement (Y)   =   35 feet
Vertical path separation at crossing point (H) =   38 feet
Time until crossing (Tc)   =   42 seconds

Probabilities:
Blind flying collision (Pn)   = 1.0×10^{-4}
No blunderer correction (Pb) = 0.71
No evader correction (Pe)   = 0.61

No self-correction (Ps)   = 0.818

Probability of collision given a blunder (Pc)   = 3.6 x 10^{-5}

A sensitivity analysis was performed by rerunning the problem with initial path separations of 3.6 to 4.5 nm. No other input data were changed. The ABRM has the capability to do these analyses automatically. The results obtained are shown in Figure 6-3. Only two values of INSEPH (4.0 and 4.1) were found that had a non-zero collision risk.
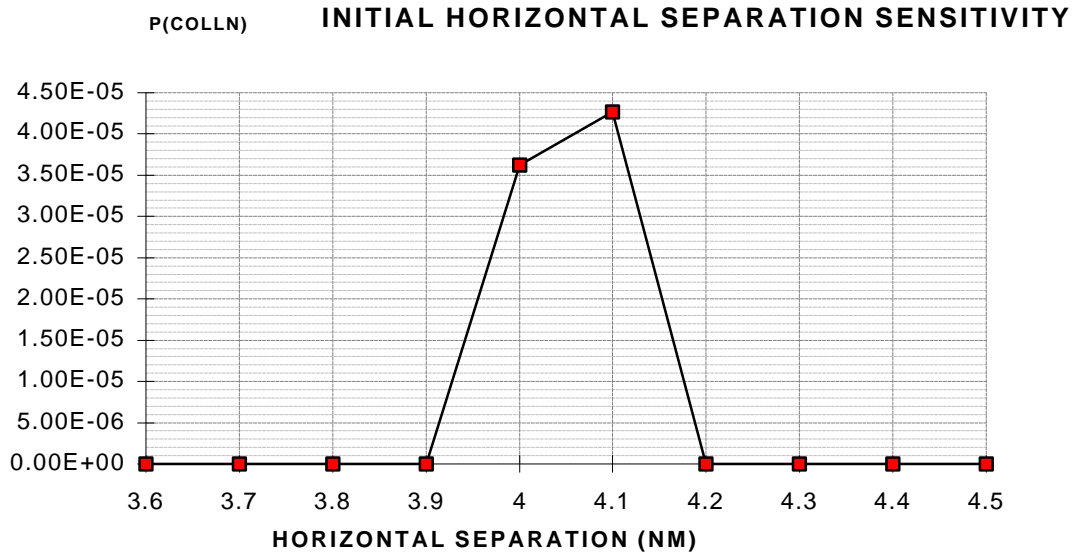
Figure 6-3
Collision Risk as a Function of Initial Horizontal Separation in The Hypothetical Example

In this example the blunderer is descending at a 4 degree angle. Increasing or decreasing the initial separation can result in the blunderer crossing safely above or below the evader's path. As a further extension of the sensitivity analysis, both the horizontal and vertical blunder angles were varied independently, as shown in Figure 6-4. The vertical angle is varied in 1 degree steps and the horizontal angle is varied in 5 degree steps. Only one point (PHI = 120 and ALPHA1 = -4) was found that had a non-zero collision risk. These 35 combinations were run on a 486 personal computer in under one minute.

BLUNDER ANGLE ANALYSIS
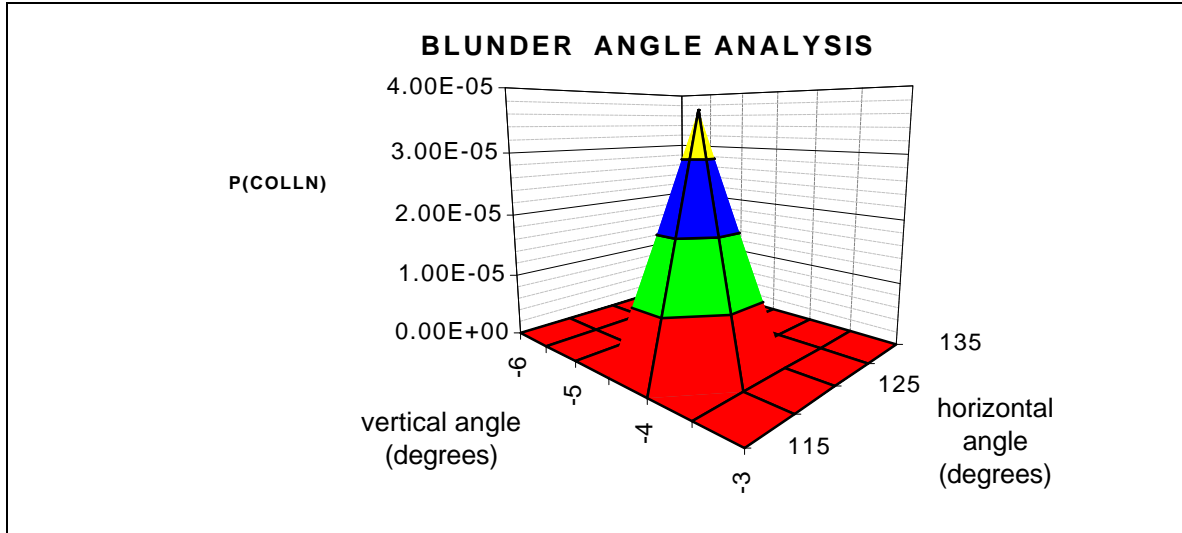
Figure 6-4
Collision Risk as a Function of Horizontal and Vertical Blunder Angles

The reader is reminded that this is only a hypothetical example, to illustrate use of the model. In order to determine the impact of a change in separation minima and/or new technology, the same scenario could be run under current conditions and modified conditions. Reduced separation requirements could impact the initial separation, increase the effective aircraft density, and reduce the self correction time (measured from the moment the blunder occurs). The result of these considerations could either increase or decrease the relative risk of collision, depending on the particular scenario. This example illustrates the power of the ABRM to analyze a risk scenario and determine the relative contributions of various factors to the overall risk.

Data Requirements

Actual data on blunder scenarios can be obtained through analysis of reports of operational errors (OEs) and pilot deviations (PDs). OEs are cases where required minimum separation was lost as a result of a failure of the air traffic control (human-technical) system. PDs are situations where separation was lost due to pilot error. Both would provide examples and estimates of the relative likelihoods of various situations where a potential risk of collision was observed and controller intervention was required, often delayed, and sometimes not provided in time.

Some data on human reaction (response) times may be obtainable through analysis of operational error and pilot deviation reports, but high-cost human-in-the-loop experiments with ATC and aircraft simulators may be also be needed to obtain the necessary data. Similar experiments have been conducted in close parallel runway approach studies. Most of the data obtained in these parallel approach studies would not be applicable to the study of en route separation safety. The air traffic controller reaction times would not be

applicable, as the en route operational environment is quite different from the terminal environment. It is less clear as to whether pilot and aircraft reaction times would differ significantly in the two environments. If time and funding for additional human-in-the-loop simulations are lacking, existing data might be sufficient for a rough estimate of relative risk.

6.2   TRAFFIC ORGANIZATION AND PERTURBATION ANALYZER (TOPAZ)

Summary

The Traffic Organization and Perturbation AnalyZer (TOPAZ) enables the evaluation of safety for a given (e.g., new) operational Air Traffic Management (ATM) concept during various flight phases. TOPAZ consists of a suite of analytical, model-based software modules, including a high-level Petri net-based simulation environment and mathematical packages to evaluate fatal ATM-related accidents. TOPAZ can incorporate probability estimates of rare deviations from normal operating conditions, which significantly distinguishes TOPAZ from commonly used, fast-time simulation environments, like the Total Airspace and Airport Modeller (TAAM).

Description

TOPAZ is a tool designed to evaluate the safety/capacity of a given (or new) operational ATM concept during various flight phases. One of the outstanding features of TOPAZ is its ability to account for the role of the human in ATM safety. The Human Operator Modeling to Evaluate Reliability, Organization and Safety (HOMEROS) module contains controller and pilot performance models that are based on E. Hollnagel's models of human cognition [R6.2]. Human behavior is modeled as a dynamic interaction between the ATM environment and a process of switching between different control modes that reflect different degrees of sophistication of human action and reliability of performance. Key factors in the switching process are the amount of perceived workload and time pressure. These models avoid the need to select between a too-conservative and a too-optimistic human reliability model.

TOPAZ consists of a suite of analytical model-based software modules that are used to evaluate an operational ATM concept. The primary modules are the following:

- A high-level, Petri net-based simulation environment, for evaluating frequencies of non-nominal event sequences. The main numerical packages are:
  - A data base of high-level Petri net modules for human, environment, and systems in ATM
  - A data base of ATM-related hazard types, frequencies, and probability densities
  - A user interface for the modular development of an application-dedicated, high-level Petri net
  - A user interface for the execution of Monte Carlo simulations

- Various mathematical models to evaluate fatal ATM-related accidents (collision between aircraft or uncontrolled flight into terrain due to crossing a wake vortex of a preceding aircraft). There are numerical packages for the following evaluation types:
  - Numerical evaluation of probability density functions of aircraft evolution with time
  - Fitting Gaussian mixtures to empirical, Monte Carlo, or numerical distributions
  - Evaluating a generalized version of the Reich collision risk model
  - Evaluating a probabilistic risk model of crossing the wake vortex of a preceding aircraft (this package is under development at NLR's Informatics division)

The execution of a safety/capacity evaluation exercise consists of three corresponding steps:

- Assess the frequency of safety-critical, non-nominal event sequences through running Monte Carlo simulations with the high-level Petri net simulator.

- Evaluate the probability of fatal ATM-related accidents (collisions between aircraft, or collision into terrain due to crossing a wake vortex of a preceding aircraft), through a subsequent use of the various packages.

- Through a spreadsheet, combine the results obtained into relevant ATM safety measures (fatal accident risks, economic risk, individual risk, and societal risk).

<u>Inputs Required</u>

In order to execute an operationally truly relevant safety/capacity evaluation of a given (new) operational ATM concept, a significant amount of input material has to be collected:

- Description of the operational ATM concept to be evaluated. This might be done up to the level of human controller tasks (air and ground), air traffic procedures, and technical ATM/CNS (Air Traffic Management / Communications, Navigation, Surveillance) systems. Starting from a less detailed description is possible. In this case, the safety evaluation results will be less precise, but when comparing conceptual designs this might even be an advantage.

- Statistical characterization of the air traffic scenarios to be evaluated; i.e. traffic flow(s), aircraft types, etc.

- Identification of all relevant hazards, including a qualitative evaluation of their effects. This is accomplished through executing a preliminary hazard analysis that pays proper attention to all possible sources of non-nominal events (human, procedural, and technical systems).

- Develop a high-level Petri net model for the operational concept to be evaluated. This high level-Petri net model should be of sufficient detail to represent all event sequences which may play a critical influence on the safety/capacity assessment.

- Identification of parameters or parameter ranges for all elements that may have a critical influence on the safety/capacity assessment. This is accomplished through collecting statistical data from appropriate data bases and through assessing the allowable ranges of the design parameters.

Outputs Produced

With the help of TOPAZ, it is, in principle, possible to evaluate the safety characteristics of any (new) operational ATM concept under consideration, with respect to safety-critical, non-nominal event sequences. The outputs provided consist of frequencies for the occurrence of non-nominal event sequences and conditional probabilities of collision (or hull loss) for different types of non-nominal event sequences. The practical interpretation of these figures is supported by a tree-wise representation, with an overall risk measure at the top. If desired, TOPAZ executes safety assessments as a function of scenario parameters, such as traffic flow.

Major Assumptions and Limitations

The main limitation is that for every instantiation of an operational ATM concept, TOPAZ will often need an appropriate adaptation of already available, high-level Petri net modules. For such adaptation, a high level of expertise is required from multiple domains (stochastic modeling, human factors, and air traffic expertise).

Computational Characteristics

TOPAZ runs on a personal computer (PC); a powerful one is preferable when running Monte Carlo simulations.

Modularity and Flexibility

TOPAZ is a highly modular and flexible system.

Status

TOPAZ is under continual development for application to advanced operational ATM concepts. In mid-1996, TOPAZ had reached a certain level of maturity for the safety assessment of Dependent Converging Instrument Approaches (DCIA) with the help of MITRE's Converging Runway Display Aid (CRDA). The most recent development has incorporated models of human cognition based on E. Hollnagel's approach to human reliability analysis [R6.2].

Extent of Model Verification

The software implementations of the high-level Petri net and the Generalized Reich collision risk models have been verified for correctness. For this, extensive use was made of the mathematical basis of these models. Beyond this level, the results obtained were corroborated through discussions with experts.

Principal Applications

- DCIA/CRDA safety assessment for Schiphol airport Amsterdam [R6.3]
- Analysis of advanced ATM concepts in Europe (to be done in TOSCA II, phase 2)
- P-RNAV route separation safety assessment [R6.4]
- Safety-based, Free Flight concept design
- Safety-based design of airport/Traffic Maneuvering Area (TMA) procedures
- Safety controllability by human operators [R6.5]
- Safety assessment of collisions due to wake vortices

Availability

TOPAZ is constantly being updated and improved. It is available through the National Aerospace Laboratory NLR in the Netherlands, PO Box 90502, 1006 BM Amsterdam. Contact: Henk Blom, phone: +31.205113544, blom@nlr.nl. The most recent information on TOPAZ can also be obtained from this source. Information about TOPAZ can also be found on the Internet. See http://www.nlr.nl/public/news/f151-01/index.html.

6.3 THE NATIONAL AIRSPACE RESOURCE INVESTMENT MODEL (NARIM)

Introduction

The National Airspace Resource Investment Model (NARIM) is being developed jointly by the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA). The purpose of NARIM is to provide NASA and the FAA with a modeling and analysis capability to examine airspace concepts associated with future advances to the United States' National Airspace System (NAS). The system is also being developed to provide a NAS perspective to the research and investment allocation process. In providing this perspective, NARIM will include the modeling and analysis of current and potential operations, the engineering impacts of future systems, and the ability to trade requirements across system and procedural investment alternatives.

NARIM consists of a collection of operational models, architecture/infrastructure models, NAS infrastructure data, demand data, and analysis tools. These functional elements are used in a coordinated manner to perform a wide variety of analyses, including but not limited, to investment alternative analysis, operational analysis, system-wide performance assessment, concept exploration, and benefit/cost analysis of proposed NAS architecture

enhancements. These tools provide a means of assessing how the system will perform under new concepts of operation.

The NARIM system consists of three interrelated components:

- Operational modeling
- Architectural/Technical modeling
- Investment analysis modeling

The first two of these components will provide invaluable information to the separation/collision Risk modeling effort.

The top level design of NARIM can be decomposed into the seven major components illustrated in Figure 6-5: environmental data, demand data, preprocessors, operational models, architecture/infrastructure models, investment analysis models, and analysis tools. Environmental data includes data pertaining to the NAS infrastructure (such as sector boundaries and subsystem performance characteristics), aircraft performance data (such as climb rates and fuel flow), and weather data. Demand data is used within the NARIM architecture to model the resultant load placed on the system for the input scenario. Preprocessors are used to convert raw demand data into a common file format that can be used by other models and analysis tools. Operational and architecture/infrastructure models are used to compute specific performance metrics and typically have a set of required inputs files, optional input files, and output files. Investment analysis models are used to compare various investment alternatives and the interaction between the associated system performance parameters. The analysis tools are usually more limited in scope and provide a detailed computation or visualization of a specific performance metric such as a proximity event.

The Models and Tools

Find Crossings (FC) is a tool used to identify the times and locations that aircraft enter and leave sectors as well as other data elements such as instantaneous sector load and average sector load. The first step in performing these computations is to generate the structured sector database which is performed by the *FC Setup* preprocessor. This step decomposes the three-dimensional airspace sectors into two-dimensional convex polygons, mapped back to the original sector, and structured to expedite the performance of *FC Run*. The structured sector database is then used in conjunction with a set of demand data (i.e., 4-D trajectories) to compute the times and locations of sector entries as well as sector utilization information. *FC Run* uses a highly optimized quad-tree algorithm to perform these computations. The output of *FC Run* includes crossings, entry points, sector statistics, and SUA activity data which are all used by other tools under the NARIM analysis framework.

Environmental Data	Demand Data	Preprocessors	Operational Models	Analysis Tools
NAS Infrastructure	ETMS (V4.2)	RT Parser	RAMS	Count Proximities
Aircraft Performance	SAR	Convert	Total Traffic Tool	Display Load
Weather	CDR	FC Setup	OPGEN	Load Compare
	OAG		Find Crossings	Point Proximity Dot Display
			Architecture/ Infrastructure Models	Leg Comparison
			NASSIM	
			Investment Analysis Models	
			Insight5D	

Figure 6-5.   NARIM Functional Elements

The *Total Traffic Tool* (T^3) is typically used in conjunction with other NARIM analysis tools to generate aircraft proximity events. Proximity events are used in NARIM analyses as an indicator of the relative complexity or controller taskloading associated with a demand scenario. T^3 requires as input a set of 4-D trajectories and, optionally, the structured sector database. T^3 output (such as identification of the first proximity event between an aircraft pair in a sector) is used for analysis purposes (such as comparing two different concepts of operations) and as input to NARIM Analysis Tools, described next.

The NARIM Analysis Tools are used to examine airspace density, proximity events, and flight leg statistics. This NARIM component consists of a series of separately compiled and executed programs. The first tool, *Count Proximities*, is used to categorize proximity events by closing velocities. Closing velocity can be used to identify the type of proximity event as being either a crossing conflict, head-on conflict, or overtaking conflict. The output of this tool is stored in an ASCII file which is typically used with other desktop tools (such as Excel) in the conduct of studies.

The second tool, *Point Proximity Dot Display*, generates a graphical display of proximity events overlaid on a map of the United States. These proximity events are usually color-coded, based upon their relative closing velocity, to indicate the relative complexity of the demand scenario being analyzed.

The third tool, *Load Compare*, is used to compare airspace density or proximity events occurrence rates across two scenarios or at different times within a single scenario. This tool requires sector statistics information computed as part of the *FC* module. Sectors can be either current sectors as defined by ACES data or can be user specified. *Display Load* creates a geographic plot of the output of *Load Compare* (such as proximity event occurrence rates, instantaneous airspace density, or airspace density over time).

The last tool, *Leg Comparison*, is used to compare, on a flight-leg-by-flight-leg basis, the difference between the two input scenarios. The metrics that are currently used in *Leg Comparison* are the average distance between flights over time and the length and duration of flight legs. However, additional metrics have been evaluated and could be included if necessary.

The *Optimized Trajectory Generator* (*OPGEN*) is used to construct wind optimized trajectories between city pairs constrained by aircraft performance, scheduled arrival times, desired time en route, and special use airspace avoidance constraints. *OPGEN* uses subroutines contained in *FC* to identify whether a flight enters a special use airspace in the baseline scenario since that identifies its availability for the wind-optimized case. The user also has the option of specifying additional constraints such as whether to impose cardinal flight altitude rules. *OPGEN* generates 4-D trajectories in the same format as *Convert* and thus they can be used interchangeably by other tools within NARIM such as *FC* and T^3. *OPGEN* is used within NARIM to generate trajectories for scenarios containing aircraft that fly point to point.

The *Reorganized ATC Mathematical Simulator* (*RAMS*) provides fast-time simulation and conflict resolution as part of NARIM's operational modeling capability. *RAMS* can perform high-fidelity investigations of aircraft conflicts that occur under different scenarios. Inputs include sector boundaries, aircraft flight plans, aircraft performance, SUA restrictions, and workload model task times. RAMS runs as a stand-alone application on the workstation and is loosely integrated with other NARIM components, meaning that its inputs and outputs are done through files. Since this model was developed and is maintained by Eurocontrol, its integration into the NARIM architecture will be limited to a stand-alone application that executes on the NARIM platform, an HP workstation.

The *National Airspace System Simulation Model* (*NASSIM*) comprises the architecture/infrastructure modeling component of NARIM. It is used to identify potential resource demand/capacity imbalances under alternative concepts of operation. The scope of the current NASSIM prototype is an ARTCC, a TRACON, and two airports. The current prototype is developed in a graphical, object-oriented development environment. Simulation objects are developed to reflect the functional behavior and performance characteristics of elements of the NAS (such as human, hardware, and software components). These objects may be modified to reflect changes in the characteristics or performance of an element of the NAS, implemented through some combination of functional enhancement and procedural changes. The objective of the current NASSIM prototype is to evaluate the impacts of data link as an alternate media for air/ground voice

communications. The model generates a wide variety of performance metrics that are stored within the model and manually extracted for use in desktop analysis tools such as Excel.

Insight5D comprises the investment analysis modeling component of NARIM. The *Insight5D* prototype incorporates a methodology, referred to as Integrated Response Surface Modeling (IRSM), used by the U.S. Department of Defense (DOD) on its advanced programs. The core concept is to build up a hierarchy of response surfaces. At each level, a surface represents the interactions and tradeoffs among system performance parameters. The values associated and the surface defined by the relationships between performance parameters is determined either through an analytic formula or through multiple runs of a simulation model. The interaction of parameters at one level will define a new set of parameters at the next higher level and a surface is developed to show the tradeoffs among these parameters. The hierarchy and the surfaces allow the decision maker to determine visually how tradeoffs can be made and how a decision at the top level is reflected in regions of tradeoffs at each lower level.

6.4   THE INTERNATIONAL CIVIL AERONAUTICS ORGANIZATION (ICAO) COLLISION RISK MODEL

The International Civil Aeronautics Organization (ICAO) provides guidance for separation analysis (e.g., [R6.6]). It has adopted a collision risk model developed by the North Atlantic System Planning Group (NAT SPG) to evaluate the safety implications of varying separation standards in the North Atlantic Oceanic Track System (NAT OTS). The newest North Atlantic separation standard (60 NM lateral and 1,000 ft vertical) was arrived at by using this model together with a set of Minimum Navigation Performance Standards (MNPS) that aircraft must meet if they intend to fly in airspace covered by the new separation minima. The model is adapted from the original Reich separation model [R6.7].

Main approach

In the collision risk scenario, one aircraft blunders from its own assigned path into airspace that is assigned to other air traffic. The collision risk is essentially the product of the probability of the blundering aircraft occupying a small volume of airspace and the probability of one of the other aircraft occupying the same airspace at the same time. The airspace occupied by an aircraft is approximated by a three-dimensional box. Equation (1) indicates the general approach to computing the probability of collision.

$$P(\text{collision}) \cong P_y(S_y) \bullet P_x(S_x) \bullet P_z \bullet [\text{traffic density factor}] \qquad (1)$$

The main factors are the lateral overlap probability $P_y(S_y)$, a longitudinal overlap probability $P_x(S_x)$, a vertical probability P_z, and a traffic density factor. The parameter S_y represents the (proposed) minimum lateral separation between adjacent oceanic tracks. The parameter S_x represents the (proposed) minimum indicated separation between

consecutive aircraft at the same altitude on the same track in the same direction. The criteria for allowing a particular separation minimum is that the probability of collision does not exceed a fixed target level of safety.

Lateral deviations are modeled as a double-double exponential probability distribution with parameters derived from historical data. This distribution is a mixture distribution that combines a probability distribution of deviations due to avionics and flight management systems with one of deviations due to blunders.

The primary model inputs are the traffic density and lateral navigation performance. Traffic density is defined in terms of same and opposite direction traffic at the same flight level. Navigation performance is defined by three terms - standard deviation, proportion of flight time exceeding 30 nm deviations, and proportion of flight time between 50 and 70 nm deviations. The output of the model is the risk of collision, expressed as the expected number of collisions per 10^7 flying hours.

6.5   BOEING ADS STUDY

The reference [R6.8] reports a study that was done by the Boeing Air Traffic Control Systems Analysis Group that addresses the application of Automatic Dependent Surveillance (ADS) to oceanic aircraft tracking.

Purpose and application

This study analyzed both lateral and longitudinal separations in the North Atlantic oceanic tracks as a part of estimating the benefits of ADS. Lateral modeling in the study slightly generalizes the work of ICAO [R6.6], Reich [R6.7], and others. The longitudinal modeling is based on the sum of three separation parameters: intervention rate, tactical control response, and surveillance accuracy. The study estimated how much more tightly oceanic traffic could be packed, both laterally and longitudinally, without compromising existing levels of safety.

Main approach

In the lateral analysis, the ICAO Collision Risk Model is used without changing its form. The probability of lateral overlap in the ICAO model is based on the assumption that 50% of large navigational errors would be detectable and correctable with ADS. The parameter α in the double-double exponential distribution is adjusted to relate ADS effects to the collision risk model.

The study estimated maximum track loading or maximum insertion rate into a single track as the rough longitudinal equivalent of lateral separation between adjacent, parallel oceanic tracks. While the lateral modeling expressions reflect probabilities of uncontrolled

overlap,[2] the longitudinal modeling uses explicit time buffers related to the tactical intervention cycle in the following operational scenario.

1. An aircraft operates without intervention until its separation from the lead aircraft decreases to or below a preset alarm distance. This alarm is a trigger point for tactical intervention by the controller, not an operational error.
2. After analyzing the situation, a controller issues tactical control instructions. The scenario assumes that the controller must use only speed control to maintain separation.
3. On receiving the tactical instructions, the pilot acknowledges the commands and executes the speed change maneuvers.
4. The time to implement the speed change includes the estimated response time of the aircraft control system.

The total initial longitudinal separation is determined as the sum of three buffers (or regions), expressed in terms of minutes: surveillance accuracy region, intervention rate region, and tactical control region. Traffic densities depend on the initial separation, but the initial longitudinal separation is not the minimum separation that the controller is required to protect. A surveillance accuracy region is sized to provide a Minimum Indicated Separation (MIS). This includes a minimum actual separation plus an allowance for inaccuracies in the indicated positions displayed on the controller's console. An intervention rate region is sized to balance the need for closely spaced traffic with the controller workload needed to deal with frequent tactical interventions. A tactical control region is sized by probabilistic addition of delays attributable to controller scanning, controller recognition, communication delay, pilot reaction, and aircraft response.

Main inputs and outputs

The starting points for this study are the same inputs and outputs used for the ICAO Collision Risk Model. The estimates of ADS detectable and correctable errors were determined by direct examination of all recorded navigational errors greater than 20 nautical miles in the North Atlantic airspace. With ADS and improved navigational accuracy, the study estimates that lateral separations could be safely reduced to as little as 30 nm. Using the longitudinal analysis, the sum of the longitudinal buffer zones was also just under 30 nm.

The factors in the intervention rate region are related as follows:

$$\mathbf{P_a(IR)} = \sum_{i \geq IR} \sum_{j > i} \mathbf{P_S(i)} * \mathbf{P_l(j)} \qquad (2)$$

---

[2] The form of the lateral equations anticipates uncontrolled overlap. As previously presented, the effect of tactical intervention can be "hidden" by changing the parameters of the navigational error probability function. Despite this, the lateral equations do not reveal the direct connection between intervention performance parameters and the resulting changes in collision risk.

where,

IR = intervention rate region (in minutes),
$P_a(IR)$ = probability of intervention alarm,
$P_S(i)$ = probability of Total Initial Longitudinal Separation of i minutes,
$P_l(j)$ = probability of separation loss of j minutes.

The tactical control region is based on the sum of random variables representing the various sources of delay. This is in contrast to making a worst-case allowance for each source and adding up all of the worst-case buffers. The result is an operational worst-case that takes into account that some delay from one source may be offset by less delay from another source. Mathematically, this requires computing the convolution of the probability density functions of an operational sequence that must take place in a given order. The safety buffer is then set by choosing a target level on the combined, cumulative probability distribution function.

The minimum indicated separation is based on the current oceanic system probability of longitudinal overlap during maximum track loading and the probability density function (PDF) f(x) expressing the accuracy of longitudinal position determination. The Minimum Indicated Separation, Sx, is determined by numerically inverting the integral formula:

$$P(Sx) = \int f(x) f(x + Sx) dx \qquad\qquad (3)$$

where,
     P(Sx) = probability of overlap given Sx

6.6   PARALLEL APPROACH BLUNDER MODELING

Here, as in the oceanic lateral modeling, a blunder refers to an aircraft that strays from its own path into the path of other aircraft. In evaluating the safety of parallel approach operations, the FAA has analyzed the consequences of a particular, worst-case blunder as an indicator of the relative safety of changes in ATC procedures and runway separation distances. Although this specific blunder scenario is referred to in a number of studies, the terms of reference are inconsistent. Within this discussion, it will be referred to as the Parallel Blunder Scenario.

Real-time Simulations at the FAA William J. Hughes Technical Center (FAATC)

The Parallel Blunder Scenario requires a controller to detect when the blundering aircraft leaves the Normal Operating Zone (NOZ) and to communicate break-out instructions to any aircraft that would be threatened by the blunder, and requires the threatened aircraft to execute the break-out maneuver. Real-time simulations at the FAATC include human interaction with trained personnel in the roles of controllers and pilots. Smaller, faster

computer models have been a useful complement to the extensive simulations at the FAATC.

The Blunder Risk Model (BRM)

The BRM was developed by Lincoln Laboratory as part of the FAA's demonstration project for the Precision Runway Monitor (PRM). The intent of the PRM program was to develop equipment, algorithms, and procedures that would allow safe operation of independent approaches to parallel runways separated by as little as 3000 feet.

Purpose and application

The BRM executes the Parallel Blunder Scenario as a Monte Carlo simulation.[3] Because it is a computer model, the BRM can execute experiments more quickly and easily than is possible with the real-time simulations at the FAATC. The BRM incorporates the definitions of events and operational requirements used in the Parallel Approach Scenario at the FAATC.

Main approach

The Parallel Blunder Scenario analyzes the situation only after a blunder has been committed. The BRM incorporates the PRM alert logic as a part of the simulation, introducing a source of random variation in the alert warnings that are available to the controllers. Human interaction times and delay distributions are required inputs to the BRM; the computer model cannot produce new information about the response times of controllers or pilots. The Monte Carlo logic used in the BRM samples one source of delay after another, in sequence, until the evader maneuver begins, or until the blundering aircraft is safely past the evader.

Main inputs and outputs

For each encounter between a blundering aircraft and an evader, the primary output is the distance between the two aircraft at the point of closest approach. The encounter geometry is based on a uniform longitudinal distribution of evader traffic and a lateral distribution based on measurement of aircraft performance at operational airports. Evader maneuvers are chosen from a fixed, discrete set of maneuvers that were observed and recorded in real-time simulations at the FAATC and elsewhere. The BRM results are summarized as a frequency distribution of minimum separations observed in the simulated iterations of the scenario.

---

[3] A Monte Carlo simulation produces a probability distribution of an output measure that depends on several statistically determined input measures. The specific approach of Monte Carlo simulation is to randomly sample from all possible combinations of the input parameters in proportion to their probability density functions in order to build up an approximate probability for the output measure.

The output measure is the minimum separation between the blundering aircraft and an aircraft using the parallel approach path. The major events in an encounter are the blunder, the warning, the intervention, the evasion, and the termination. The minimum separation distribution is analyzed to determine if the intervention performance is adequate to protect the parallel approach stream from a worst-case blunder. Intervention performance is measured by a resolution time random variable computation shown in equation 4.

$$t_{res} = t_{alert} + t_{cont} + t_{comm} + t_{pilot} \tag{4}$$

where,

t_{alert} = time from the blunder to the alert or warning
t_{cont} = time from the alert to when the controller issues an instruction
t_{comm} = communications delay in message transmission
t_{pilot} = time from ATC message receipt until the aircraft starts to turn

6.7   ICAO REQUIRED NAVIGATION PERFORMANCE (RNP)

Required Navigation Performance (RNP) is a method used to specify the navigation performance required by aircraft for a particular operation. The method was originally developed by ICAO and applied to oceanic, en route, and terminal area operations [R6.9]. It also is being developed for application to approach and landing operations [R6.10].

Purpose and application

As applied in the lateral separations between established routes, RNP specifies the 95% lateral navigation performance accuracy. This value is then used to determine the spacing (separation) between parallel routes, where the larger the 95% value, the greater the required spacing. Also factored into the spacing is the rate at which large navigation errors occur.

As applied to approach and landing operations, RNP specifies both a 95% performance accuracy and an outer boundary, which specifies aircraft performance with a 10^{-7} probability. For approach, these limits are applied to both the lateral and vertical dimensions. The outer boundary is related to the obstacle clearance surfaces. Unlike en route, there has not been a proposal to use the approach RNP to establish separation requirements.

6.8 THE REDUCED AIRCRAFT SEPARATION RISK ASSESSMENT MODEL (RASRAM)

Overview

The Reduced Aircraft Separation Risk Assessment Model (RASRAM) is a collision risk analysis tool that describes scenario outcomes in a fault tree framework that includes dynamic, time-budget, and probabilistic computations in addition to the static risk factors normally included in fault trees [R6.12]. The objective of RASRAM is to link aircraft separation standards and intervention procedures to quantitative safety risk. The model provides an analysis framework suitable for comparing the risks of current procedures with risks associated with applications of new technology and reductions in aircraft separation standards. Fault tree presentations make it easy to understand how accident and incident risks are distributed among the contributing elements.

RASRAM development is being performed for NASA, in coordination with the FAA, as an integral part of NASA's Terminal Area Productivity (TAP) program. Initial safety risk assessments have been performed for flight scenarios related to final approach, landing, and roll-out for parallel and single runway operations. These scenarios are the lateral blunder scenario, runway occupancy/incursion scenario, and the wake vortex scenario. The final result for each scenario is a consolidated risk of incident and accident from all sources directly applicable to the scenario.

Good agreement has been obtained among several of the predicted risks and actual incident and accident statistics. This provides a level of confidence that the baseline safety results can be used to provide a relative comparison of the safety of proposed new procedures with the safety of current operations and technologies. The safety associated with independent parallel approaches using the Precision Runway Monitor (PRM) has been quantified previously. Using RASRAM, the safety of further separation reductions for parallel approaches based on the application of new technologies can be analyzed. The RASRAM computational methodologies that resolve conflict geometries in the lateral blunder scenario can be generalized to scenarios anywhere in the terminal area or en route airspace.

RASRAM produces a variety of risk measures. In the lateral blunder scenario, there is a fairly well established baseline safety level for the risk of a Near Midair Collision (NMAC). For possible en route scenarios there is, as yet, no consensus on target measures of safety. The approach used in RASRAM quantifies the connection between a number of risk measures. In this way, RASRAM can remain useful as the aviation safety community explores different alternatives for target measures and levels of safety.

Computing Miss Distances for a Blunder into a Stream of Traffic

The RASRAM static risk factors are computed and presented in Excel spreadsheets. A commercially available mathematical analysis program called Mathcad is used to compute the probabilities of time-dependent events. A prototype graphical user interface (GUI) is available to allow a user to interact with the model and vary the parameters of the scenarios. All of the software runs on a laptop personal computer.

The physical quantity of interest for the lateral blunder scenario is miss distance, which is the distance between two aircraft at their point of closest approach. The Mathcad equations model a fixed flight path for a blundering aircraft that violates a separation criteria, triggering an alert. In response to this blunder, miss distance probabilities are computed for all potential positions of "evader" (i.e., other, non-blundering) aircraft following a common trajectory. The probabilities include the path and timing of an evasion maneuver made at some delay time after the alert is triggered.

The key input parameters for the lateral blunder scenario are as follows.

The blunder maneuver: speed and linear trajectory,
The evasion maneuver: speed, original trajectory, turn rate, and turn angle,
Distance between the evaders and the alert point,
Total Navigation System Error,
Total delay time (controller, communications, pilot, aircraft), and
Traffic density on the evader stream.

In the GUI, scenario visualization is aided by a simple (cartoon) animation of the encounter geometry. Miss distance probabilities are shown in graphical form and incorporated as risk factors in the fault tree summaries of the scenario. The completed fault tree is available for display, along with selected summary tables.

6.9   THE AIRSPACE SIMULATION AND ANALYSIS FOR TERPS (ASAT) SYSTEM

The Airspace Simulation and Analysis for TERPS (ASAT) System is a multifaceted computer tool for aviation related simulations and evaluations. ASAT simulates various operational scenarios in realistic environments consisting of single or multiple aircraft, pilots and air traffic controllers. ASAT consists of high fidelity models and empirical data representing each component of real life scenarios, including aircraft, geographical, environmental, navigation systems, ATC systems and human factors models. ASAT uses these models to generate realistic aircraft positions in time and space and produces statistical data for risk analysis studies and visual representations.

ASAT has been used to evaluate the feasibility and safety associated with various operational requirements, including multiple airport interaction problems, the multiple parallel approach program, converging approaches, procedural issues, required navigation

performance evaluations, GPS, and GPS/WAAS. The ASAT System can be modem linked to essentially any full motion certified aircraft simulator, so that real-time data can be collected, played back, or analyzed. Monte Carlo simulations can be built using continuous distributions developed from real-time data, which accurately reflect the behavior of the aircraft, pilots, air traffic control, and associated subsystems.

Because all ASAT modules have been validated against the benchmarks of the industry, ASAT is the benchmark modeling tool within the FAA. Additional material about ASAT may be found in Section 5.4.

6.10   TOTAL AIRSPACE AND AIRPORT MODELLER (TAAM)

Summary

The Total Airspace and Airport Modeller (TAAM) enables the evaluation of safety (conflicts and other separation infringements), capacity (number of movements, etc.), and economic effects (fuel flow and direct operating costs) of a given (new) operational Air Traffic Management (ATM) concept or airport design. TAAM uses a suite of analytical, model-based software modules and a very advanced ATC simulation engine with powerful graphics. TAAM can randomly modify the traffic used in a simulation in order to test the scenarios for different traffic situations. TAAM can also incorporate different weather and wind conditions in a simulation. These factors have a great influence in "Free Flight" scenarios in which aircraft change flight paths, depending on wind and weather conditions, without first notifying Air Traffic Control (ATC).

Description

TAAM is a tool designed to evaluate the safety/capacity and economic effects of a given new operational ATM or airport concept. The tool is built to represent the complete ATC system by means of objects. This means, for example, that an ATC controller or pilot is represented as an object in the model. The default actions of those individuals can be changed by InCa (Interpreted 'C' for aviation) scripts. As a result, new ATC systems can easily be tested or evaluated by a TAAM simulation. The human factors and the human behavior components of this model can be easily modified for a simulation by using InCa Scripts.

In order to conduct an evaluation of an operational ATM or airport concept, TAAM uses a suite of analytical and simulation based software modules. The important ones are:

- Conflict detection and avoidance module (including a powerful rulebase for conflict avoidance strategies),
- Ground movement module (gate, de-icing, taxi, runway),
- En route module (including pilot/controller interaction),

- Traffic Maneuvering Area (TMA) module (building approach and departure procedures), and
- Aircraft performance model.

Inputs Required

- Description of the ATM concept to be evaluated.
    - This might be done down to the level of the human controller, air traffic procedures, and technical ATM/CNS systems as well as new airborne equipment.
- Traffic sample (traffic flow, aircraft mix, etc.),
- Identification of all relevant hazards, including a qualitative evaluation of their effects, and
- Identification of parameters or parameter ranges for all elements that may have a critical influence on the safety/capacity assessment (e.g., weather).

Output produced

The output of the Model can be as detailed as a complete flight record of every or any given flight. This means that there is access to information equivalent to the so-called black box of an aircraft. In general, only summarized data values are used to evaluate a concept.

The main data outputs are:

- Number and type of conflicts in a given area or ATC-sector,
- Workload for the controller/coordinator,
- Workload for the flight crew (pilot),
- Capacity (number of flights per sector, throughput, delay) ,
- Fuel flow and Direct Operating Costs (DOC),
- Utilization of airspace,
- Graphical presentation of simulation
- Taxi times and gate allocations,
- Runway usage,
- Runway utilization, and
- Ground delay/taxi delay.

Limitations of the Model

No matter how accurately one represents the real-world in a simulation, one has to abstract some domains of the model. Therefore, a simulation can only be a near-real-world representation of an entire ATC system. While one can model human and weather factors in this model to some extent, their representations will not exactly mirror the real world.

Computational Characteristics

TAAM runs on a variety of UNIX workstations: Currently HP, SUN, and SGI are supported by TAAM. The number of aircraft and the scale of the simulation area are only limited by the hardware. On a Sun Ultra II with Creator 3D and 256 MB RAM, a day of U.S. traffic (90,000 flights) has been modelled.

Modularity and Flexibility

TAAM is a highly modular and flexible system which can be customized by InCa scripts.

Status

TAAM is under continual development to improve its capabilities. A TAAM User Group was formed in 1993 and has since then requested over 100 improvements to the previous version of TAAM (Version 2.9). The new version incorporates user requests and includes state-of-the-art simulation and programming techniques. TAAM 3.0 has been completely re-written in order to make it object oriented and more flexible for the users.

TAAM 3.0 will be officially released for airspace studies on January 1, 1998, and on June 1, 1998, for ground and airport simulations. It is currently under Beta test by DFS in Germany and FedEx in the U.S.

ACKNOWLEDGMENTS

Material in Section 6.3 is based on material in the "NARIM Design Document." Material in Sections 6.4 - 6.7 was excerpted from [R6.11].

List of References

R6.1 Geisinger, Kenneth, "Airspace Conflict Equations," *Transportation Science*, Vol. 19, No. 2, May 1985, pp. 139-153.

R6.2 Hollnagel, E., *Human Reliability Analysis Context and Control*, Academic Press, London, 1993.

R6.3 Everdij, M.H.C., G.J. Bakker and H.A.P. Blom, *Application of Collision Risk Tree Analysis to DCIA/CRDA Through Support from TOPAZ*, NLR contract report, 1996.

R6.4 Everdij, M.H.C., G.J. Bakker, P.J.G. Blanker & H.A.P. Blom, *Designing EATMS Inherently Safe,* TOSCA II WP 4, Eurocontrol, NLR, 1997.

R6.5 Biemans, M.C.M. and J. Daams, *HOMEROS: Human Operator Modelling to Evaluate Reliability, Organisation and Safety*, RHEA/TH/WPR/6/1, European Union DGVII, Contract number AI-95-SC.107, NLR, 1997.

R6.6 ICAO (International Civil Aviation Organization), *Air Traffic Services Planning Manual*, Doc 9426-AN/924, 1984. Amendments dated 15 Aug 85, 11 Sep 85, 3 Nov 88. Montreal, Quebec, Canada.

R6.7 Reich, Peter G., "Analysis of Long-Range Air Traffic Systems: Separation Standards--I, II, and III," *The Journal of (the Institute of) Navigation*, Vol.19 (1966), No. 1, pp. 88-96; No. 2, pp. 169-176; No. 3, pp. 331-338.

R6.8 Coote, M. A., G.W. Schraw, and R.W. Schwab, "Oceanic Requirements and Benefits Modeling for Automatic Dependent Surveillance (ADS)," *Air Traffic Control Quarterly*, Vol. 1(1) (1993) pp. 31-57, New York, NY: John Wiley & Sons, Inc.

R6.9 ICAO (Internation Civil Aviation Organization), *Manual on Required Navigation Performance (RNP).* Doc. 9613-AN/937. Montreal, Quebec, Canada, 1994.

R6.10 AWOP, *Fifteenth Meeting of the All Weather Operations Panel,* ICAO, 26 September - 12 October 1994. Montreal, Quebec, Canada.

R6.11 Shepherd, Roger, Rick Cassell, and Edwin Alphonso, "Reduced Aircraft Separation On Final Approach - A Review Of Separation Risk Models" Alexandria, VA: Rannoch Corp., 1996 (draft report).

R6.12 Shepherd, Roger, Rick Cassell, Rajeev Thapa, and Derrick Lee, "A Reduced Aircraft Separation Risk Assessment Model," *Proceedings of the AIAA Guidance, Navigation, and Control Conference, New Orleans, August 10-13, 1997*.

Additional References for Model Evaluation (re: TOPAZ)

- Bakker, G.J. and H.A.P. Blom, *Air Traffic Collision Risk Modelling*, Proc. 32nd IEEE Conf. on Decision and Control, December 1993, pp. 1464-1469 (NLR report TP 93292 U).
- Blom, H.A.P. and G.J. Bakker, *A Macroscopic Assessment of the Target Safety Gain for Different En-Route Airspace Structures within SUATMS*, NLR report CR 93364 L, 1993.
- Everdij, M.H.C., M.B. Klompstra, H.A.P. Blom & O.N. Fota, *Final Report on Safety Model, Part I: Evaluation of Hazard Analysis Techniques for Application to En-Route ATM*, NLR report TR 96196 L, December 1995.
- Everdij, M.H.C., M.B. Klompstra & H.A.P. Blom, *Final Report on Safety Model, Part II: Development of Mathematical Techniques for ATM Safety Analysis*, NLR TR 96197L, 1996.
- Everdij, M.H.C., G.J. Bakker and H.A.P. Blom, *Application of Collision Risk Tree Analysis to DCIA/CRDA through Support from TOPAZ*, NLR contract report, 1996.
- Everdij, M.H.C., H.A.P. Blom and M.B. Klompstra, *Dynamically Coloured Petri Nets for Air Traffic Management Safety Purposes*, Proc. 8th IFAC Symposium on Transportation Systems, Crete, Greece June 1997 (Pre-print available from NLR).

[This page intentionally blank.]

7.0 FACTORS POTENTIALLY AFFECTING SEPARATION SAFETY
(Factors That May Need To Be Included In The Model)

7.1 INTRODUCTION

As separation minima shrink, many factors that have negligible impact on safety when separations are large assume vital importance. Because of the many safeguards and redundancies built into airspace systems, the probability of a midair collision is extremely small. If a midair collision does occur, it is likely the result of a very rare combination of events. Therefore, to properly model the risk of a midair collision in an environment of reduced separation, it is necessary to consider the impact of rare events and even rarer combinations of events. A wake turbulence encounter also may pose a hazard depending on other factors.

For many, there is a strong propensity to dismiss both the possibility of rare events and rare combinations of events and the possibility that these might result in an accident. Indeed, even the most thoughtful and pessimistic individual cannot think of all possible hazardous rare events.

To model the risk of a midair collision or serious wake vortex encounter in an environment of reduced separations, one must decide what factors are important to include in the model. It is therefore necessary to first identify factors that *might* be critical in accurately determining such risk. The Separation Safety Modeling Team has begun the development of a list of such factors.

The list is in outline form. The subject headings were chosen for convenience—other headings might serve as well. The placement of factors under a heading is often arbitrary—often a factor might well fit under a number of headings. Thus, the headings do not imply mutual exclusivity. A factor listed under one heading should perhaps be listed under other headings as well, but to save space, we have tried (but not always succeeded!) to minimize this. However, some factors appear under more than one category because they may take on a slightly different meaning under each. The order does not imply expected importance.

Although not shown here, interactions and time dependencies among factors in different parts of the outline will occur—some of these are the unfortunate ones that cause accidents. This outline is certainly not a complete list, but it contains more factors than could be considered explicitly in any feasible risk model. Part of the modeling task is to determine which of the factors and interactions are the critical ones.

A more realistic display of the factors would be in the form of a network or circuit diagram with lines linking factors that might potentially interact. The difficulty with this is that if all factors are included, the diagram becomes illegible. Another form of constructing large-scale models, where hundreds of variables play a role, is the use of causal diagrams. Causal diagrams are used in the Systems Dynamics methodology developed by J. Forrester

in the early sixties. This technique is particularly well suited for models where all the variables in the model have time dependencies.

One final remark with respect to the independence of factors. Often, it appears that two or three factors are independent of each other—that the occurrence of one has no effect on the (probability of) occurrence of others. There may, however, be another, supposedly exogenous factor, that can influence all of the others. Consider the case of an airline with poor management, one which spends as little as possible on training and maintenance. This airline may hire a maintenance company with similar predilections, may postpone maintenance and repair, and may not adequately train its pilots or ground crews. In such a case, a ground crew error, for example, might suggest greater than usual probabilities of maintenance problems and pilot errors: "Corporate Culture" counts!

The following pages present our current outline of factors that might influence the risk of a midair collision. The outline is a "work in progress"— it undoubtedly will be revised over time. This outline is also reproduced, with annotations, in Appendix A. The annotations provide invaluable insights into the reasons some factors are important and also provide additional, useful information.

7.2 FACTORS THAT MAY INFLUENCE SEPARATION SAFETY

Interactions among these factors must also be considered, as must be the possibility that "exogenous" factors might impact more than one of the primary safety-related factors.

      A. Relative aircraft positions and velocities (encounter geometry)
         1. "Blind-flying" risk [factors that affect risk—no intervention]
            a. Horizontal and vertical positions and closing angles
            b. Aircraft velocities and accelerations
            c. Climb/descent rates and accelerations
            d. Vertical path separation at crossing point
         2. Pilot intervention - factors that affect timely pilot detection and correction
            a. Closure rate
            b. Relative bearings and aspect angles in relation to cockpit field of view restrictions, the horizon.
            c. Rate of change of the above angles (zero for linear collision courses)
            d. Aircraft attitudes and bank angles
             e. Meteorological conditions and background conditions, including location of the sun (affecting ability to perceive other aircraft and their relative distance, velocity, and trajectory)
            f.   Natural lighting conditions (e.g., day, night, dawn, dusk)
            g. Threat aircraft size, skin color, and lighting
            h. Condensation trails
            i. Empty visual field
            j. Night accommodation
            k. Party line

l. Reliance on ground-based surveillance and procedures
m. Cockpit workload, staffing, automation, and procedures
n. Flight crew training, skill, teamwork
o. TCAS/ACAS responsiveness (affected by aircraft bank angle, ...)

> *It should be noted that, in accordance with the guidance given in ICAO Annex 11, the carriage of ACAS by aircraft within a region should not be used to justify a reduced separation minimum. However, the presence of such systems may be relevant when contemplating the application of reduced separations as changes to the ACAS systems may be required in order to avoid an unacceptable rate of false alerts.*

3. ATC intervention - factors that affect the probability of timely and effective ATC intervention
    a. Air traffic service provided
    b. Climb/descent rate and acceleration (affects ATC computer projections)
    c. Horizontal velocity and acceleration
    d. Turn rate and turn acceleration (change in turn rate)
    e. Airspace complexity
    f. Traffic complexity and density
    g. Proximity to an airspace boundary (e.g., SUA)
    h ATC coordination (e.g., involving an aircraft in hand-off or point-out status.)
    i. Air traffic management tools for reducing controller workload and improving controller intervention capability
        1) Automated controller planning tools including trajectory projection, conflict probe, and conflict resolution
        2) Automated out-of-conformance alerts (3 D) (which alert ATC to any deviation of an aircraft from its nominal path).
        3) Controller display quality: picture, information, and presentation of information
    j. Controller skill, training, and teamwork
    k. Controller workload, staffing, and procedures
4. Aircraft reaction - factors that affect aircraft reaction time in response to a needed maneuver
    a. Aircraft performance (including maneuverability)
    b. Pressure and density altitude (related to aircraft performance and atmospheric conditions)
    c. Speed (e.g., relative to stall speed, available thrust, etc.)
    d. Climb/descent rate
    e. Attitude and bank angle
    f. Proximity to terrain

B. ATC rules and procedures; airspace structure
    1. Hemispheric rules

2. Route structure, i.e., the use of parallel or non-parallel ATS routes and whether they are bi-directional or uni-directional
3. Separation minima
   a. Horizontal
   b. Vertical
   c. How often values close to the "official" separation minima are used in practice
4. Flight planning
   a. Requirement to file flight plan
   b. Requirement to fly in conformance to flight plan
   c. Requirement to cruise at certain discrete altitudes -- Hemispheric rules
5. Requirement to obtain clearance prior to altitude change
6. Positive control
7. Airspace complexity and flight path geometries, including the following:
   a. Traffic demand pattern
   b. Number of aircraft at same altitude
   c. Numbers and locations of crossing tracks
   d. Amount of traffic operating on opposite direction tracks
   e. Amount of traffic transitioning altitudes
   f. Nature of the aircraft population (i.e., the diversity of traffic with respect to aircraft performance and equipage, such as the mix of various speeds, climb performance, and desired optimal flight levels)
   g. Peak and average traffic demands versus system capacity
   h. Runway capacities and the limitations of associated ground services
   i. Any adjoining special use airspace, airspace usage, and types of activities including the civil/military mix
   j. Regional meteorological conditions (e.g., the prevalence of convective storms, etc.)
8. Designated airspace classifications.
9. Flow management capability (ability to control traffic input to ATC)
   a. Strategic air traffic flow management
   b. Tactical air traffic flow management
   c. Ad hoc ATC "in trail" restrictions or enhancements
   d. Procedural restrictions (e.g., by local operating procedures).
10. Special airspace restrictions
    a. Restricted airspace
    b. Special use airspace
    c. Traffic flow restrictions
    d. Noise abatement restrictions
11. Special situations
    a. Air shows
    b. Other aviation-intensive events (e.g., Olympics)
    c. Military exercises
    d. Formation flight
12. Backup procedures

C. Communication capability
   1. Direct controller/pilot voice communication (VHF/HF/SATCOM)
   2. Indirect controller/pilot voice communication (HF)
   3. Controller/pilot data link communication (CPDLC)
   4. Controller/controller voice and automated data link communication, both inter and intra ATS unit(s)
   5. Data link between ground ATC automation systems and aircraft flight management computers
   6. System availability, reliability, and capacity
   7. Backup systems and procedures

D. Aircraft
   1. Certification standards
      a. Airframe
      b. Power plant
      c. Systems
   2. Maintenance [including manuals]
      a. Airframe
      b. Power plant
      c. Systems
   3. Airplane/power plant [applies for normal operation and abnormal operation (loss of engine, or failure of some airplane systems)]
      a. Speed and altitude envelope of the airplane type [This factor may contribute to exposure frequency in cruise operation in a given airspace.]
      b. Climb and descent profiles (speed/thrust/altitude profiles) [may affect exposure frequency in climb and descent]
      c. Maneuver response capability (e.g., to a controller or TCAS/ACAS alert), such as:
         i. Engine spool up time
         ii. Airframe inertia
         iii. Rate of climb or descent
         iv. Level acceleration/deceleration
      d. Airplane dimensions and wake vortex profile
   4. Airplane systems factors
      a. Navigation sensor compliment
         i. ADF
         ii. VOR
         iii. DME
         iv. IRS (newer, strap-down inertial reference systems)
         v. INS (older, gimbaled inertial reference systems)
         vi. Loran
         vii. Omega
         viii. Satellite-based systems such as GPS, GLONASS

    ix. Other
   b. Navigation systems
    i. Navigation computer system
    ii. Other, like-capability area navigation (RNAV) systems (on other aircraft)
    iii. Navigation System Performance
     1) Required navigation performance (RNP)
      a) Typical and non-typical performance (e.g., MASPS/MOPS; RTCA SC-181 documents)
      b) Time-keeping accuracy.
     2) Reliability/availability
     3) Integrity
     4) Effects of more accurate navigation
      a) "Unfortunate" interaction of pilot blunder/altitude misassignment and more accurate navigation (i.e., a blunder would be more likely to put one aircraft right on top of another because of the more accurate horizontal navigation provided by GPS)
   c. Communications capability
    i. Voice communications systems
     1) Commercial aircraft
      a) Required communication performance
      b) VHF systems (direct)
      c) HF systems (indirect)
     2) Military aircraft
     3) General Aviation and other aircraft
     4) UHF
     5) SATCOM (communication via satellite)
    ii. ADS-B
    iii. ACARS
   d. Surveillance capability
    i. Required surveillance equipment performance
    ii. Air-ground transponder
     1) Mode C transponder
     2) Mode S transponder
     3) Mode A transponder
    iii. TCAS/ACAS (Traffic Alert and Collision Avoidance System/Airborne Collision Avoidance System)
    iv. Advanced TCAS/ACAS, such as TCAS IV
    v. Automatic dependent surveillance (ADS)
    vi. Cockpit display of aircraft traffic information (CDTI)
   e. Backup systems and procedures

  E. Ground/Satellite systems: Surveillance and Navigation
   1. Surveillance capability

   a. Procedural dependent surveillance
      i. Content of pilot position reports
     ii. Reporting intervals
   b. Automatic dependent surveillance (ADS)
      i. Basic update rate
     ii. Display accuracy; controller display target position error
    iii. ADS contracts (e.g., increased reporting rate by triggering events)
    iv. Sensor accuracy
     v. System reliability
    vi. System availability
   vii. End-to-end communications time capabilities
  viii. System coverage
   c. Independent surveillance (radar)
      i. Type of sensor (primary or secondary)
     ii. Coverage area
    iii. Processing and associated delays
    iv. Accuracy of measured position after processing
      1) Radar registration error (Mosaic
      2) Slant-range error for non-Mode C equipped aircraft
     v. Update rate
    vi. Display accuracy (error)
   vii. System reliability.
  viii. System availability
    ix. Backup systems

2. Performance
   a. Accuracy
      i. Automation-induced errors
   b. Reliability/availability
   c. Integrity
      i. Automation-induced errors
     ii. False positives
    iii. Missed events
   d. Equipment outage
      i. Backup systems, including power
      1) Availability
      2) Reliability
      3) Integrity
     ii. Backup procedures
   e. External interference
      i. Natural
     ii. Human
      1) Sabotage
      2) Spoofing
      3) Jamming

       f. Processing, data transmission, and associated delays (e.g., delay between acquisition of a signal and the display of the information)

F. Human performance
   1. Flight crew performance/skill
     a. Monitoring/situational awareness
     b. Crew coordination and communication/Cockpit Resource Management
     c. Controller/Pilot communication/coordination
          (Also see section F.2.c. of this outline)
     d. Response time
     e. Movement time
     f. Crew workload and vigilance
     g. Human error/human reliability
     h. Interaction with hardware/software automation/assistance
       i. Displays
       ii. Warnings/advisories
         1) TCAS
         2) CDTI
     i. Certification standards
     j. Training
     k. Operator procedures, manuals
     l. Corporate culture
   2. Air Traffic controller performance/skill
     a. Monitoring/situational awareness
     b. Decision making
     c. Controller/pilot communication/coordination
          (Also see section F.1.c. of this outline)
     d. Controller/controller communications and coordination
     e. Controller Response Time
     f. Controller Workload
     g. Interaction with displays/automation/decision aids
       i. Displays
       ii. Automation
      iii. Decision Aids
      iv. Warnings/advisories
         1) Flight path prediction
         2) Conflict probe
     h. Controller errors
     i. Training
     j Corporate culture

G. Environment
   1. Visibility
     a. Day/night/dusk/dawn
     b. Ceiling

    c. Sun position

    d. Clouds

    e. "Background" (i.e., against which pilot is to locate other aircraft)

2. Adverse weather, storms

3. Turbulence, wind shear

4. Special problems (e.g., volcanic ash)

5. Wake vortex (may cause turbulence or engine problems for following aircraft at same or lower flight levels)

[This page intentionally blank.]

8.0   DATA NEEDS AND MODEL CALIBRATION

8.1   THE REQUIREMENT FOR DATA

In order to provide a reasonably accurate output, any model used to estimate collision risk for an air traffic management (ATM) system must be based on reliable system data. Where data are unavailable, it may be necessary to estimate values for input parameters, which can lead to a very high level of uncertainty in results. The lack of data can, therefore, restrict the applicability and reliability of a collision risk model.

8.2   SOURCES OF DATA

The availability and source of data for risk modeling depends on the type of situation being modeled. When modeling an existing system, data can be obtained by direct observation, although this may be expensive and time consuming. An example of this is the collection of data on traffic levels and lateral track-keeping errors that is undertaken for the annual risk assessment for the North Atlantic region. Another example is the measurement of aircraft height-keeping performance at high altitudes, done as part of a study of the feasibility of reducing vertical separation minima above FL 290.

Obtaining reliable data for hypothetical systems can be much more difficult. For such systems, it may be necessary to estimate many of the important performance parameters. This results in high levels of uncertainty in the risk estimates. For this reason, it is much easier to assess risk for existing systems (or existing systems with small modifications) than for completely new concepts of air traffic management.

The best source of data for collision risk modeling is information taken directly from current systems. Such data fully reflect the actual performances of all parts of the systems. It is usually possible to obtain reliable estimates for the error in data values obtained from observations. This allows the error in the final risk estimates to be assessed.

Failing "real" data, system specifications can be used as a source of model input parameters. The greatest problem with specification data, particularly for engineered systems, is that the real performance is often much different (better or worse) than the designed performance. This may result in overly pessimistic or optimistic risk estimates - sometimes by orders of magnitude.

A final source of information which is commonly used is simulation, real- or fast-time. However, information from simulations can be very misleading: Simulations can contain many hidden assumptions about how the system will behave and real-time (i.e., human-in-the-loop) simulations can only model a limited number of potential situations. Simulations should, therefore, be considered part of the modeling process rather than a source of (real-world) input data.

8.3   TYPES OF DATA

For the purpose of collection, data for risk modeling can be divided into three general categories as follows:

- Physical data on the system,
- Equipment performance data, and
- Human performance data.

Physical data on an ATM system include such items as aircraft sizes and speeds, flow rates, route structures, separation standards, etc. Equipment performance data include both normal and abnormal performance such as the normal variability in aircraft navigation and radar failure rates. Human performance data include the capability and reliability of the human elements of the system. These three components are not entirely independent and, in practice, it is not always possible to completely distinguish system performance from human performance.

In general, the collection of physical data on the system to be modeled is the most straightforward, both for existing systems and for future systems. The most difficult physical data to obtain for future systems is the traffic demand pattern. Predicting traffic demand for future scenarios can require highly complex models.

Equipment performance data can be obtained either from direct observations of operating systems or from performance specifications. The preferred method is to use observational data. Performance specifications may be overly pessimistic or optimistic, as mentioned above and are also often not sufficiently detailed for risk modeling. For instance, Required Navigation Performance (RNP) specifications require aircraft navigation systems to ensure that aircraft remain within some containment range of their nominal position for 95% of the time. Unfortunately, it is the 5% of time that the aircraft may spend outside of the containment range which dominates the risk. The nature of these large errors has to be assumed in the absence of any actual data.

For existing systems, equipment performance data can be fairly easy to obtain. For instance, radar and radio telephony (RT) failures are routinely recorded by ATC authorities.   Also, quite detailed aircraft performance data are available for the aircraft of some manufacturers. Some types of data, however, may require specific data collection exercises. An example of this is the collection of aircraft height-keeping performance being undertaken for the application of a Reduced Vertical Separation Minimum (RVSM) in the North Atlantic. This required a major international effort to develop and operate a complex monitoring program.

The collection of human performance data is the most difficult area. A significant amount of work has been done in other industries, such as nuclear power generation and the chemical process industry, and also on aircrew performance, but little has been done in air traffic control.   The frequency with which human error is cited as a major cause of

aviation accidents highlights the importance of this factor. Some data on human error can be obtained from records for existing systems. For instance, the frequency with which pilots fail to follow clearances in the current system can be obtained. There are, however, serious problems in terms of under-reporting these types of events and this must be taken into account in any analysis. That is, these reports probably cannot be used to obtain statistical estimates of the frequencies of such events. The reports and, in particular, their narratives can provide a rich source of qualitative information on the types of human errors that can occur and the circumstances surrounding their occurrences.

Accident and incident reports often contain data on two or all three of the categories listed at the beginning of this section. Accidents, for example, usually result from a combination of failures or inadequacies, human and system, and the environment in which these failures occur may also be relevant.

8.4 DATA REPOSITORIES

There is a virtually unlimited number of aviation data repositories. Many developed nations track and retain a wide variety of aviation data. Difficulties arise in the use of these data as a result of data idiosyncrasies, incompleteness, and inconsistencies, both within a data base and among data bases. As a result, if one is not totally familiar with all aspects of the data generation process, one may use "rational" assumptions about the data that are, in fact, incorrect. Coded data may, for example, reflect the state of knowledge of the coder or the politics of the organization at the time of coding. Accident investigators may honestly differ in the interpretation of physical data, with consequent differences in reported causal factors. Data may be incomplete in that they are missing, or data values may reflect incomplete records, such as a "shortened" flight time resulting from a flight track being "timed out" by a computer. It is thus incumbent on the analyst to become as familiar as possible with the data being used and with the processes that were used to collect and refine/process the data.

It is impossible to list any substantial fraction of the aviation data bases. To give some idea of the wide variety of data available, provided below are two examples of FAA data repositories, each of which includes several data bases that originate with a variety of FAA organizations.

8.4.1 The National Aviation Safety Data Analysis Center (NASDAC)

NASDAC is a repository of several safety-related data bases. It includes several software tools to assist analysts in extracting data relevant to their interests. As described above, care must be taken in using these tools because of the idiosyncratic nature of data and, therefore, it is recommended that the analyst seek the assistance of the Center's staff in the use of the repository. The Center is located in the headquarters building of the FAA in Washington DC. Much of the Center's data are also available on the Center's Web site at http://nasdac.faa.gov/safety_data/. Among the data bases included in this repository are the following:

- The *National Transportation Safety Board (NTSB) Aviation Accident/Incident Database* is the official repository of aviation accident data and causal factors. In the database, an event is classified as an accident or an incident. "Aircraft accident" means an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight and until all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage. The NTSB defines "incident" as an occurrence other than an accident, associated with the operation of an aircraft, which affects or could affect the safety of operations. The NTSB database contains only selected incident reports. Source: NTSB; update frequency: monthly.

- The *FAA Incident Data System* contains a much more extensive collection of records of events that do not meet aircraft damage or personal injury thresholds contained in the NTSB definition of an accident. Source: FAA; update frequency: monthly.

- The *Aviation Safety Reporting System (ASRS)* is a voluntary, confidential, and anonymous incident reporting system. It is a cooperative program established under FAA Advisory Circular No. 00-46D, funded by the FAA, and administered by the National Aeronautics and Space Administration (NASA). Information collected by the ASRS is used to identify hazards and safety discrepancies in the National Aviation Airspace System. It is also used to formulate policy and to strengthen the foundation of aviation human factors safety research. Source: NASA; update frequency: quarterly.

- The *Near Midair Collisions System (NMACS) Database* includes the special category of aviation incidents known as NMACS. Separate reporting and investigation procedures have been established for this category of incident. The technical definition of a NMAC is an incident associated with the operation of an aircraft in which a possibility of collision occurs as a result of proximity of less than 500 feet to another aircraft, or where a collision hazard existed between two or more aircraft. A report does not necessarily involve the violation of regulations or an error by the air traffic control system, nor does it necessarily represent an unsafe condition. Because NMACs are reported by pilots or other crew members, some of the information may represent the reporter's subjective interpretation of what occurred, and because the motivation to report differs among pilots and crews, the number of events reported probably does not represent the total universe of NMAC events. Source: FAA; update frequency: monthly.

- *NTSB Safety Recommendations to the FAA with FAA Responses*. The NTSB uses the information it gathers during accident investigations and the determination of probable cause to make safety recommendations to all elements of the transportation industry. While the recipient of a recommendation does not have to implement the proposed action, it does have to respond formally to the recommendation and specify what action is, or is not, being taken, and why. This database contains the NTSB Safety

Recommendations to the FAA with FAA Responses. Source: FAA; update frequency: monthly.

- The *Bureau of Transportation Statistics (BTS) Airline Traffic Statistics* spreadsheet contains traffic and capacity statistics on individual airline operations. Statistics presented include departures, hours flown, and miles flown by airline, by year.

- The *International Safety Recommendations Database* contains the safety recommendations from aviation authorities of Canada, the United Kingdom, and the United States. This database is a project of the "International Data Exchange for Aviation Safety" (IDEAS) group.

- The *Aviation Safety Statistical Handbook* contains information on national airspace incidents and accidents. Data in tabular and graphical format are presented for near midair collisions (NMACs), operational errors (OEs), operational deviations (ODs), pilot deviations (PDs), vehicle/pedestrian deviations (VPDs), runway incursions (RIs), and aircraft accidents. Data are presented for 1991 through 1996.

8.4.2   Performance Monitoring Analysis Capability (PMAC)

PMAC is a data analysis tool that provides improved accessibility to airline operations and airport data in a PC environment. PMAC, Version 2.0, has three main modules:

- Airport Demand: PMAC captures scheduled demand from the Official Airline Guide (OAG) and unscheduled demand from military and general aviation (GA) flights.

- Airport Delay: Delays consist of the following phase-of-flight delays: gate delay, airborne delay, taxi-in delay, and taxi-out delay. Also, arrival delays with gatehold and without gatehold (scheduled flight time versus actual flight time) and flight times are presented.

- NAS Performance: NAS Performance Summary Reports (annual/monthly demands, delays, cancellations), airport attributes (forecasts, fleet mix, taxi times), and general reference information (weather, airport capacities, national groundhold programs).

Key databases that are integrated and filtered in PMAC include:

- Airline Service Quality Performance (ASQP),
- Enhanced Traffic Management System (ETMS),
- Terminal Area Forecast (TAF),
- Official Airline Guide (OAG), and
- National Climatic Data Center (NCDC) weather data.

PMAC, Version 2.0, resides in stand-alone mode on two Pentium PC workstations in the FAA's ASD-400 computer laboratory. The front-end graphical user interface (GUI) runs

in Windows 3.1 with Visual Basic 4.0 and works in conjunction with supporting add-on tools such as First Dimension, True Grid 4.0, and Crystal Reports 5.0. Its relational database, FOXPRO 2.6, operates on the back-end and maintains all data files. PMAC presently contains complete 1995, 1996, 1997, and partial (2-month lag) 1998 data sets of delay, demand, weather, cancellation, and diversion data. System Query Language (SQL) features are also available in the PMAC group through ACCESS, FOXPRO, and VISICALC. PMAC is scheduled to be operational in a Windows NT platform by May 1998.   Information on PMAC may be accessed on the FAA ASD-400 Web Site at http://www.faa.gov/asd/: First click on "Operations Research" and then on "NAS Performance Models and Tools."

8.5   MODEL VALIDATION

In addition to providing input parameters to a risk model, data are also important for validating the risk estimates produced. Validation is a particularly difficult aspect for risk models for air traffic systems because the required safety performance is extremely high. This means that it is not possible to validate a model's predictions against actual accident occurrence data. To partially overcome this problem, risk models may be used to predict more frequent events that are precursors to accidents. For instance, data on serious losses of separation could be collected and compared with the results predicted by the model. Data on such events can be obtained from existing systems and used to partially validate the performance of the model. Another validation technique is to compare results from two, independently developed models that use different approaches to estimate risk.

APPENDIX A

AN ANNOTATED OUTLINE OF
FACTORS POTENTIALLY AFFECTING SEPARATION SAFETY
(Factors that may need to be included in the model)

[This page intentionally blank]

This outline was presented in Section 7 of this report. In this version, many of the individual factors are annotated with additional explanatory material and information. (The additional material is presented in italic text bounded by square brackets.) As was stated before, the subject headings of the outline were chosen for convenience—other headings might serve as well. The placement of factors under a heading is often arbitrary—often a factor might well fit under a number of headings. Thus, the headings do not imply mutual exclusivity. A factor listed under one heading should perhaps be listed under other headings as well, but to save space, we have tried (but not always succeeded!) to minimize this. However, some factors appear under more than one category because they may take on a slightly different meaning under each. The order does not imply expected importance.

Although not shown here, interactions among factors in different parts of the outline will occur—some of these are the unfortunate ones that cause accidents. This outline is certainly not a complete list, but it contains more factors than could be considered explicitly in any feasible risk model. Part of the modeling task is to determine which of the factors and interactions are the critical ones.

One final remark with respect to the independence of factors. Often, it appears that two or three factors are independent of each other—that the occurrence of one has no effect on the (probability of) occurrence of others. There may, however, be another, supposedly exogenous factor, that can influence all of the others. Consider the case of an airline with poor management, one that spends as little as possible on training and maintenance. This airline may hire a maintenance company with similar predilections, may postpone maintenance and repair, and may not adequately train its pilots or ground crews. In such a case, a ground crew error, for example, might suggest greater than usual probabilities of maintenance problems and pilot errors. In other words, interactions (dependencies) among these factors must also be considered, as must the possibility that "exogenous" factors might impact more than one of the primary safety-related factors.

An Annotated Outline Of Factors Potentially Affecting Separation Safety

A. Relative aircraft positions and velocities (encounter geometry)
    1. "Blind-flying" risk [factors that affect risk—no intervention]
        a. Horizontal and vertical positions and closing angles
        b. Aircraft velocities and accelerations
        c. Climb/descent rates and accelerations
        d. Vertical path separation at crossing point
    2. Pilot intervention - factors that affect timely pilot detection and correction
        a. Closure rate
        b. Relative bearings and aspect angles in relation to cockpit field of view restrictions, the horizon.
            *[Aircraft design dictates available **field of view**; small windshields and side windows, interior fitments (HUD mount, sunshades) that intrude into the field and external aircraft structure (wing, nose, propeller etc.) all limit the pilot's ability visually to acquire targets. The prudent pilot takes pains to clear the area into which the aircraft is being flown; this is particularly true when a radical change is being made in the velocity vector. The relative bearing of the target from the pilot's eye must be within the field of view if visual detection is to be achieved. Windshield dirt can adversely affect the field of view; since squashed bugs are the primary source of windshield disfigurement, time of year may be a factor.]*
        c. Rate of change of the above angles (zero for linear collision courses)
            [Rate of change of relative bearing: aircraft in rectilinear flight on a collision course maintain a fixed bearing relative to each other thus reducing probability of early detection. If either subject aircraft or target is maneuvering, then judgment of collision risk becomes more complex.]
        d. Aircraft attitudes and bank angles
            [The attitude of the target aircraft can be a cue to relative motion between subject aircraft and target in close proximity, and maneuver also reduces the value of these data. Even in steady state flight, interpretation of target attitude can be difficult.]
        e. Meteorological conditions and background conditions, including location of the sun (affecting ability to perceive other aircraft and their relative distance, velocity, and trajectory)
            [The background, or whatever lies beyond the target within the field of view, affects the pilot's ability to acquire the target. Military aircraft are camouflaged for a reason and they are very difficult to detect against like-colored surface features. Above the horizon, at least by day, all aircraft appear black when they are distant, increasing the chance of acquisition. Visual ranges of 30 miles are not uncommon. As the target closes, its skin color may have an effect and this variable

should be considered for collision intervention, especially for large targets.

Discharge tube anti-collision lights are very effective enhancers of visual acquisition, whatever the background, even in daylight. Since any beacon can be intermittently masked from the viewer by target aircraft structure and since flash duration is very short, some manufacturers offer "synchronized" flashers which seek to ensure that lights do not all flash at the same time.

At night, a bright star field or a field of lights on the ground can effectively prevent visual detection of targets in all phases of flight.

Fighter aircraft attack out of the sun for a reason; looking in the direction of the sun will almost always deny the pilot visual acquisition of targets and can materially affect vision for some time afterward.

Meteorological effects can severely hamper visual acquisition; clearly, the pilot cannot be expected visually to detect a target at a range greater than the prevailing visibility. However, especially at high altitude, it is often difficult for the pilot to know the value of the visibility because of the lack of visual reference. What may appear to be almost zero visibility can actually be 3 or 4 miles. In these circumstances, the pilot's lookout may be less vigilant than it would be in clear air since it may be assumed that nothing can be detected in the conditions.]

f. Natural lighting conditions (e.g., day, night, dawn, dusk)

g. Threat aircraft size, skin color, and lighting

h. Condensation trails

> *[Can significantly enhance visual acquisition. Equally, the apparent disappearance of a target as it passes out of the Mintra band can result in confusion, especially if the pilot is unused to estimating how far the target travels in given time. In such a circumstance, a persisting trail can draw the attention away from the target's current position.]*

i. Empty visual field

> *[Although, clearly, there is more risk of collision in busy airspace, visual acquisition may be more effective in a multi-target environment than in one where a target appears only occasionally. If the pilot has no outside visual stimulus, his eyes' focal distance "defaults" to a point not far ahead of the aircraft. In "inside a light bulb" meteorological conditions, it can be difficult to know when the eye is focused at a distance commensurate with early detection.]*

j. Night accommodation

> *[When I was taught to fly, I learned that cockpit lighting should be kept as low as possible to improve my ability to see beyond the windshield in night operations. This idea seems to have gone out of the window (excuse the weak pun). Particularly in cruise, pilots tend to turn up*

the lights and conduct their business as if there were no risk of collision.]

    k. Party Line

        [Pilots tend to listen to radio communications in their area and may learn valuable information concerning ETAs and altitudes of proximate aircraft, thus improving situational awareness. The value of this technique should be quantified.]

    l. Reliance on ground-based surveillance and procedures

        [Collisions are very rare, and pilots may be complacent with the success rate of radar systems and the procedures used in remote areas. It is a sure bet that pilots are more vigilant when flying in Africa or India than over Cleveland, despite the variation in traffic density.]

    m. Cockpit workload, staffing, automation, and procedures

    n. Flight crew training, skill, teamwork

    o. TCAS/ACAS responsiveness (affected by aircraft bank angle, ...)

        It should be noted that, in accordance with the guidance given in ICAO Annex 11, the carriage of ACAS by aircraft within a region should not be used to justify a reduced separation minimum. However, the presence of such systems may be relevant when contemplating the application of reduced separations as changes to the ACAS systems may be required in order to avoid an unacceptable rate of false alerts.

3. ATC intervention - factors that affect the probability of timely and effective ATC intervention

    a. Air traffic service provided

    b. Climb/descent rate and acceleration (affects ATC computer projections)

    c. Horizontal velocity and acceleration

    d. Turn rate and turn acceleration (change in turn rate)

    e. Airspace complexity

    f. Traffic complexity and density

    g. Proximity to an airspace boundary (e.g., SUA)

    h ATC coordination (e.g., involving an aircraft in hand-off or point-out status.)

    i. Air traffic management tools for reducing controller workload and improving controller intervention capability

        1) Automated controller planning tools including trajectory projection, conflict probe, and conflict resolution

        2) Automated out-of-conformance alerts (3 D) (which alert ATC to any deviation of an aircraft from its nominal path).

        3) Controller display quality: picture, information, and presentation of information

    j. Controller skill, training, and teamwork

    k. Controller workload, staffing, and procedures

4. Aircraft reaction - factors that affect aircraft reaction time in response to a needed maneuver

     a. Aircraft performance (including maneuverability)
     b. Pressure and density altitude (related to aircraft performance and
        atmospheric conditions)
     c. Speed (e.g., relative to stall speed, available thrust, etc.)
     d. Climb/descent rate
     e. Attitude and bank angle
     f. Proximity to terrain

B. ATC rules and procedures; airspace structure
  1. Hemispheric rules
  2. Route structure, i.e., the use of parallel or non-parallel ATS routes and
     whether they are bi-directional or uni-directional
  3. Separation minima
     a. Horizontal
     b. Vertical
     c. How often values close to the "official" separation minima are used in
       practice
  4. Flight planning
     a. Requirement to file flight plan
     b. Requirement to fly in conformance to flight plan
     c. Requirement to cruise at certain discrete altitudes -- Hemispheric rules
  5. Requirement to obtain clearance prior to altitude change
  6. Positive control
  7. Airspace complexity and flight path geometries, including the following:
     a. Traffic demand pattern
     b. Number of aircraft at same altitude
     c. Numbers and locations of crossing tracks
     d. Amount of traffic operating on opposite direction tracks
     e. Amount of traffic transitioning altitudes
     f. Nature of the aircraft population (i.e., the diversity of traffic with respect
       to aircraft performance and equipage, such as the mix of various
       speeds, climb performance, and desired optimal flight levels)
     g. Peak and average traffic demands versus system capacity
     h. Runway capacities and the limitations of associated ground services
     i. Any adjoining special use airspace, airspace usage, and types of activities
       including the civil/military mix
     j. Regional meteorological conditions (e.g., the prevalence of convective
       storms, etc.)
  8. Designated airspace classifications.
  9. Flow management capability (ability to control traffic input to ATC)
     a. Strategic air traffic flow management
     b. Tactical air traffic flow management
     c. Ad hoc ATC "in trail" restrictions or enhancements
     d. Procedural restrictions (e.g., by local operating procedures).
  10. Special airspace restrictions

    a. Restricted airspace
    b. Special use airspace
    c. Traffic flow restrictions
    d. Noise abatement restrictions
   11. Special situations
    a. Air shows
    b. Other aviation-intensive events (e.g., Olympics)
    c. Military exercises
    d. Formation flight
   12. Backup procedures

  C. Communication capability
   1. Direct controller/pilot voice communication (VHF/HF/SATCOM)
   2. Indirect controller/pilot voice communication (HF)
   3. Controller/pilot data link communication (CPDLC)
   4. Controller/controller voice and automated data link communication, both inter and intra ATS unit(s)
   5. Data link between ground ATC automation systems and aircraft flight management computers
   6. System availability, reliability, and capacity
   7. Backup systems and procedures

  D. Aircraft
   1. Certification standards
    a. Airframe
    b. Power plant
    c. Systems
   2. Maintenance [including manuals]
    a. Airframe
    b. Power plant
    c. Systems
   3. Airplane/power plant [applies for normal operation and abnormal operation (loss of engine, or failure of some airplane systems)]
    a. Speed and altitude envelope of the airplane type [This factor may contribute to exposure frequency in cruise operation in a given airspace.]
    b. Climb and descent profiles (speed/thrust/altitude profiles) [may affect exposure frequency in climb and descent]
    c. Maneuver response capability (e.g., to a controller or TCAS/ACAS alert), such as:
     i. Engine spool up time
     ii. Airframe inertia
     iii. Rate of climb or descent
     iv. Level acceleration/deceleration
    d. Airplane dimensions and wake vortex profile

[The physical dimensions are parameters considered by the ICAO collision risk model]

4. Airplane systems factors
   a. Navigation sensor compliment
      [The number and "quality" of these units varies; newer digital systems typically have superior performance]
      i. ADF
      ii. VOR
      iii. DME
      iv. IRS (newer, strap-down inertial reference systems)
      v. INS (older, gimbaled inertial reference systems)
      vi. Loran
      vii. Omega
      viii. Satellite-based systems such as GPS, GLONASS
      ix. Other
   b. Navigation systems
      i. Navigation computer system
         [Most in-production commercial airplanes have these systems which include "multi-sensor" navigation systems, which combine inertial with "best position" estimation algorithms based on complimentary or Kalman filtered estimation algorithms]
      ii. Other, like-capability area navigation (RNAV) systems (on other aircraft)
      iii. Navigation System Performance
         1) Required navigation performance (RNP)
            a) Typical and non-typical performance (e.g., MASPS/MOPS; RTCA SC-181 documents)
            b) Time-keeping accuracy.
         2) Reliability/availability
         3) Integrity
         4) Effects of more accurate navigation
            a) "Unfortunate" interaction of pilot blunder/altitude misassignment and more accurate navigation (i.e., a blunder would be more likely to put one aircraft right on top of another because of the more accurate horizontal navigation provided by GPS)
      [iv. Details about navigation systems
         1) Navigation system guidance may be 2-D or 3-D, use a reference path to generate simple deviation, or more sophisticated flight director "commands." The most sophisticated systems allow "coupled" operation to a flight control computer. For flight management systems, this coupled operation is provided in flight management systems

through the "engagement" of LNAV (two-dimensional) or VNAV (three-dimensional) operation. The guidance "mode" of operation is correlated with the "pilotage" or "flight technical error" of the aircraft.

2) *Navigation data bases are provided in the more sophisticated systems. These may be updated on a 28-day cycle to keep currency with navigation charting. Data bases may be regional or international. Data bases typically contain radio navigation aid positions, published navigation waypoint locations, and terminal procedures (standard departure and arrival routes, approach transitions, published holding locations, etc.) For air carrier operations the navigation data base is specified in the ARINC 424 document. Navigation data bases allow lower workload "loading/changing" of the flight plan with reduced probability of waypoint definition error.*

3) *Navigation displays may include digital maps which provide the flight crew with a plan view display of the aircraft position and flight plan selected for the flight. A map provides "situational" awareness and helps detect errors in flight plan entry of procedures.*

4) *Required navigation performance systems are among the newest-generation of navigation systems. These systems provide an estimate of position uncertainty (the current actual navigation performance estimate (a 95% probability of being within the estimated value) together with associated levels of integrity and availability of the navigation function. RTCA SC-181 has developed the standards for RNP-based navigation.]*

c. Communications capability
  i. Voice communications systems
    1) Commercial aircraft
      a) Required communication performance
      b) VHF systems (direct)
          [VHF systems are "line of sight" limited, but of high availability when in coverage. Concern about frequency congestion of the VHF links is leading to consideration of reduced channel spacing and digital radios for voice communications.]
      c) HF systems (indirect)
          [HF systems are used for out-of-coverage communications, over the ocean, for example. They are of lower availability and (typically) there are transmission delays between aircraft and ATC controller.]
    2) Military aircraft
    3) General aviation and other aircraft

4) UHF
5) SATCOM (communication via satellite)

ii. ADS-B

iii. ACARS

[Provides digital data communications, primarily between pilot and airline operational control. A few ATC applications are used over ACARS (pre-departure clearance) and others have been proposed. Satellite systems for long-range voice communications are beginning to be used in oceanic operations. These systems provide direct controller-to-pilot (CPDC) data communications. Other potential future data link communications media have been proposed, such as the Mode S data link and the use of Low Earth Orbiting satellites (LEOs) to support ATC data communications. Additionally, the Aeronautical Telecommunications Network (ATN) is being developed as a system of protocols (open system) and routers to provide inter-operability of communications media between airplane and air traffic control.]

[iv. Remarks

Required communications performance is under development by RTCA and EUROCAE to provide high-level performance specification of air-ground communications for operation in a given airspace. Factors to be considered include message delay, availability, and integrity.]

d. Surveillance capability

i. Required surveillance equipment performance

ii. Air-ground transponder

[supports operation in controlled airspace]

1) Mode C transponder
   [Provides the ATC-assigned aircraft identification (which may not be unique) and pressure altitude quantized (rounded) in 100-ft. increments].

2) Mode S transponder
   [Provides a unique aircraft-associated identification, potential for other data transmissions, and pressure altitude quantized in 25-ft. increments.]

3) Mode A transponder
   [Provides only ATC-assigned identification (which may not be unique)]

iii. TCAS/ACAS (Traffic Alert and Collision Avoidance System/Airborne Collision Avoidance System)
   [Interrogates transponders of near-by aircraft to determine proximity, relative trajectories and relative velocities, and to provide collision avoidance advisories. TCAS, by ICAO mandate, cannot be used as a basis of reduced separation standards, but does affect risk of collision. TCAS II is required on all part 121

aircraft with more than 30 passenger seats. TCAS I, a less sophisticated system is required on air carriers with 30 seats or fewer.]

    iv. Advanced TCAS/ACAS, such as TCAS IV
    [A proposed system that would provide better sensor (intruder azimuth and range) data and horizontal, as well as vertical resolution advisories.]

    v. Automatic dependent surveillance (ADS)
    [Provides an automatic data link transmission of current aircraft state (position, velocity, etc.) information to air traffic control via satellite. Standards for a second form of ADS, the broadcast ADS, or ADS-B, are being developed by RTCA SC-186 and EUROCAE. ADS-B will permit broadcast of state data to nearby aircraft as well as ground stations. Intent information may also be provided.]

    vi. Cockpit display of aircraft traffic information (CDTI)
    [These concepts and standards are being developed to provide the display of "other traffic" information to the flight crew. Two methods of obtaining traffic data for CDTI have been proposed: the use of an ADS-B system for direct aircraft-to-aircraft data link, and the use of a Traffic Information Service (TIS) ground-to-air data link to broadcast radar track data for proximate aircraft.]

    [vii. Remarks

        1) The concept of required monitoring performance has been chartered to SC-186 to determine the accuracy, latency, integrity, and availability requirements and available performance for maneuvering aircraft flying in different ATC environments.

        2) Other future concepts for airplane system developments include provisions for airborne conflict probe and conflict resolution systems.]

  e. Backup systems and procedures

E. Ground/satellite systems: surveillance and navigation
  1. Surveillance capability
    a. Procedural dependent surveillance
      i. Content of pilot position reports
      ii. Reporting intervals
    b. Automatic dependent surveillance (ADS)
      i. Basic update rate
      ii. Display accuracy; controller display target position error
      iii. ADS contracts (e.g., increased reporting rate by triggering events)
      iv. Sensor accuracy
      v. System reliability
      vi. System availability
      vii. End-to-end communications time capabilities

   viii. System coverage
  c. Independent surveillance (radar)
   i. Type of sensor (primary or secondary)
   ii. Coverage area
   iii. Processing and associated delays
   iv. Accuracy of measured position after processing
    1) Radar registration error (MOSAIC)
    2) Slant-range error for non-mode C equipped aircraft
   v. Update rate
   vi. Display accuracy (error)
   vii. System reliability.
   viii. System availability
   ix. Backup systems
 2. Performance
  a. Accuracy
   i. Automation-induced errors
  b. Reliability/availability
  c. Integrity
   i. Automation-induced errors
   ii. False positives
   iii. Missed events
  d. Equipment outage
   i. Backup systems, including power

    [Unfortunately, backup systems, including power systems, have occasionally failed. If separation minima are reduced, backup systems play an especially critical role for, in their, absence there may not be time to depend solely on backup procedures or "kluged" work-arounds before a collision occurs.]

    1) Availability
    2) Reliability
    3) Integrity
   ii. Backup procedures
  e. External interference
   i. Natural
   ii. Human
    1) Sabotage
    2) Spoofing
    3) Jamming
  f. Processing, data transmission, and associated delays (e.g., delay between acquisition of a signal and the display of the information)

F. Human performance
 1. Flight crew performance/skill
  a. Monitoring/situational awareness

[In everyday parlance, situation awareness refers to the up-to-the-minute cognizance required to operate or maintain a system. Because the concept involves tracking processes or events in time, it can also be described as mental bookkeeping¾ keeping track of multiple threads of different but interacting sub-problems as well as the influences of the activities undertaken to control them. Breakdowns in situation awareness can lead to operational difficulties in handling the demands of a dynamic, event-driven environment. In aviation circles, this is known as "falling behind the plane." Situation awareness is generally most in jeopardy during periods of rapid change and where the confluence of forces make an already complex situation even more complex or attention demanding.

As a result, when the pace of operations increase (e.g., in more dense airspace) difficulties in maintaining situation awareness can reduce the pilot's ability to anticipate potential problems. Understanding these attentional dynamics relative to task complexity and how they are affected by computer-based systems in the cockpit is an important topic for progress in aiding situation awareness.]

b. Crew coordination and communication/Cockpit Resource Management

[The loss of situation awareness may affect not only the individual pilot, but also impact the shared awareness of the crew. As a result, the crew's ability to maintain a shared frame of reference or common situation assessment can break down, degrading communication and coordination. Breakdowns in shared awareness is particularly serious in more dynamic and complex flight contexts, where effective coordination and communication across crew members is needed to cope with non-routine or unexpected events. Poor crew coordination and communication often have been implicated in major airline accidents. This has underscored the need for crew coordination procedures and for crew members to monitor and cross check the actions of each other. These accidents have highlighted the need to consider crew performance as well as individual performance.

c. Controller/pilot communication/coordination

(Also see section F.2.c. of this outline)

[In today's environment, controller-pilot communication is a common occurrence. Pilots receive, acknowledge, and request clearances to make changes in altitude or flight paths, receive and transmit information on weather, and receive notice of radio frequencies to use in transitioning between sectors and facilities. Controllers issue instructions to change courses when potential or actual conflicts arise and when aircraft may enter restricted airspace. Problems in communication sometimes occur as a result of non-standard nomenclature, confusion as to whom a message is for, and messages being "stepped on," either as a result of the short delay between the time a microphone is physically activated and the time the electronic

activation actually occurs, or as the result of an "open" microphone preventing communication by others. Some of these difficulties should be mitigated with the introduction of data link and unique aircraft identification codes.

Clearly, communication and coordination difficulties between pilots and controllers may contribute to air traffic control (ATC) errors. This is more likely in an ATC environment in which the management of traffic is distributed differently than in today's highly-centralized, ground-based system. Tracking aircraft behavior and system status becomes more difficult if it is possible for the pilot, for example, to interact with the system without the need for or consent of the controller. This problem becomes most obvious when an experienced pilot and controller develop different strategies for resolving a problem. When they have to arbitrate, it becomes particularly difficult for them to maintain awareness of the history of interaction with the system, which usually determines the response to the next interaction. With the advent of "Free Flight" and the requirement for distributed management (division of functionality between ground and air), teamwork, as reflected in verbal and electronic communication between controllers and flight crews, is likely to be a critical component in aviation safety. Further, as more automation is introduced, it is essential that its effects on teamwork and inter-personal communication be evaluated.]

  d. Response time

[Response time generally represents the delay in responding due primarily to the time needed to organize a response. It has long been accepted that response times are fastest when one has to respond to a single event and are slowest when one has to respond to multiple events with a separate response to each. In the latter situation, the individual is required to discriminate among events and then choose the appropriate response. Furthermore, temporal and event uncertainty increase response time by increasing the demands to search among alternatives and sustain attention. Moreover, the effects of uncertainty or unpredictability are not fixed but will reflect the state of training and skill of the individual. Nevertheless, there appears to be a maximum or upper limit to response times in situations similar to those that require a quick pilot response. Response times rarely exceed one second, regardless of the amount of temporal or event uncertainty that the pilot might confront.]

  e. Movement time

[A pilot's skilled response can be divided into two phases: The first involves the pilot's preparation for a response (response time), while the second involves the actual movement time necessary to execute the response. Movement time and response time are controlled by separate aspects of the task at hand. First, the amplitude of the

movement and the requirements for accuracy interact in determining the speed of movement. Secondly, if feedback information is needed to monitor the movement, it will reduce the speed of movement. Nevertheless, feedback (e.g., visual, kinesthetic) provides for the processing and correction of subsequent responses during ongoing performance. In short, movement time is governed by the total amount of information that a pilot has to process.]

f. Crew workload and vigilance

[Underlying the effects of workload on performance is the need to handle several sources of information concurrently and the ability to alternate between these sources of information (i.e., time-sharing). The effects of workload on performance can be accounted for reasonably well by assuming that one can perform a task best when one is somewhere between very low and very high periods of activity. In other words, there is some optimum level of workload for an individual to achieve maximum performance, and both greater and lower levels of workload will impede this performance. Too low a level of workload can result in a loss of vigilance, while too high a level will result in narrowing attention to the more central or frequently occurring signals and neglecting less probable sources of information. In the inflight environment, this is equivalent to restricting one's focus to a single aspect of a problem or event at the expense of maintaining a more comprehensive internal representation or "picture" of the situation inside and outside the flight deck. In each case, what is lost is the ability of the pilot or crew to look ahead or prepare for what could come next. This becomes more critical in high density or complex traffic.]

g. Human error/human reliability

[Pilot errors or blunders are generally symptomatic of underlying mismatches between the pilot and the larger system in which the error occurred. The growing complexity on the flight deck and the current environment of "increasing efficiency" may be creating more opportunities for mismatches. For example, the increasing demands for greater capacity and efficiency in ATC will increase pressure on the pilot. In other words, the envelope of safe functioning may be reduced due to external demands, thereby increasing the potential for blunders. As another example, technological advances in the flight deck could lead to a reduction in perceived risk and hence to performance that is closer to the minimum acceptable limits, thereby effectively reducing the margin of safety. Alternately, increased automation leads to relying on different sets of skills, creating the potential for new kinds of errors (or blunders) and system failures. Accordingly, we need to consider how different technologies can either mitigate or increase susceptibility to incorrect or erroneous actions by

a flight crew. In short, we need to design technologies that assume the existence of error.]

h. Interaction with hardware/software automation/assistance

   i. Displays

[The ability of a display to reduce complexity is measured in terms of how effective it is in providing a meaningful and coherent picture of the traffic situation to the pilot. On the other hand, the need to improve readability, to use or not use color, and to reduce information clutter are more commonly cited issues by display engineers. However, the extent to which a display succeeds is not based on how little or how much information there is, but on how effectively it is arranged and integrated. Displays must be able to manipulate the data so that the resulting organization is (immediately) meaningful with respect to the problem solving tasks confronting the pilot.]

   ii. Warnings/advisories

[The use of flight deck systems that display nearby traffic and communicate warnings directly to the pilot of impending conflicts and collisions may enhance safety under reduced separation minima. However, experience with existing technologies, such as TCAS II, confirms pilot aversion to false warnings, and, hence, the possibility that a pilot may ignore a correct warning, believing it to be false. (High false alarm rates may also result in cases of "creative disablement.") Thus, to be effective in enhancing safety, these systems must have very high integrity: The display of traffic must be very accurate, and the rate of detection of impending conflicts and collisions must be very high, while the false alarm rate must be relatively low.

For a given technology, increasing detection rates generally covary with increasing false alarm rates. Even for sensitive warning systems, with high detection rates and low false alarm rates, the likelihood that a warning signal is indicative of a true collision/conflict could be quite low as a result of where the system's alerting threshold is set (lenient or strict) and the frequency of occurrence of actual collision/conflict events (the a priori probability of a conflict or conflict base rate). As a result, only a small proportion of warnings may represent true collision/conflict events. These and other factors, such as the fact that these systems cannot anticipate unexpected maneuvers by other aircraft can also conspire to reduce the effectiveness of collision/conflict warning systems.]

On-board detection and warning systems also affect the nature of air traffic control and controller-pilot relationships, as described below.

   1) TCAS

[TCAS provides flight crews with a visual display of traffic as well as aural warnings and commands. This has been one approach to mitigating the consequences of separation errors and avoiding midair collisions, particularly in congested areas (e.g., terminal areas). Despite its important alerting function, TCAS also changes the nature of the interactions between controllers and pilots, since the controller is not privy to the cockpit information provided by the system. In terms of automation, TCAS illustrates how an automated system can isolate critical items of situation awareness information that are required by both controllers and pilots. Accordingly, more effective use of such systems may require the need for increased pilot-controller interaction to share this information.

Although TCAS is proving to be a valuable tool for collision avoidance, it can add uncertainty to air traffic control and reduce the level of team-work achieved. TCAS also provides a good example that the false alarm question is not trivial. TCAS suffered considerably in its early development from problems of excessive false alerts that resulted in mistrust and lack of pilot usage. Although its detection and warning algorithms have been refined, TCAS integrity is still limited by the limitations in position information available from its antennas and vertical position and rate information derived from the 100-foot-quantized altitude reports of Mode C.].

2) CDTI

[An important technology to appear on the flight decks of the future is the Cockpit Display of Traffic Information (CDTI). The form this display finally takes will depend on pilot responses to the various kinds of displays and the application of dynamic display design principles. Without expert attention to human factors, CDTI technology could induce new pilot errors and thus diminish rather that improve safety. For example, pilots have the most difficulty in assessing the likelihood that two aircraft are on a collision course when the two flight paths are curved and when the other aircraft is approaching from a large relative bearing. Further, pilots show a strong tendency to execute maneuvers in the horizontal rather than the vertical plane. This tendency could be design-induced if the display emphasizes the horizontal layout of traffic rather than the vertical layout. Other factors to be considered include the division of responsibility for traffic separation and collision avoidance between ground-based controllers and flight crews.

Overall, the evidence tends to favor CDTI as an improvement to flight safety. It is obviously important that pilot performance with systems such as CDTI be studied carefully before they become standard operational equipment on flight decks. The impact on the pilot-controllers relationship and on separation safety must also be evaluated.]

    i. Certification standards

    j. Training

[There is the general realization that proper teamwork, reflected in verbal communications among the crew, is a critical component in maintaining safety in flight.. As in other technologies, a high percentage of human errors involves breakdowns in communication, coordination, and group decision making. Crew resource management training is effective in improving team coordination in flight crews. Nevertheless, though improved training, and better procedures, help, they will never eliminate human errors completely. Accordingly, the introduction of technological improvements must include improvements that support the detection and correction of errors that do occur, and flight crews must have the training necessary to enable them to work effectively with new procedures and technology.

With the exception of TCAS/ACAS, training, even in flight simulators, seldom is used to provide skills in infrequently encountered tasks associated with collision risk. Also, pilots may enter the workforce with an embedded behavior of keeping their attention focused inside the cockpit.]

    k. Operator procedures, manuals

    l. Corporate culture

2. Air Traffic controller performance/skill

    a. Monitoring/situational awareness

[Situation awareness in air traffic control is more vulnerable (and more difficult to achieve) in a crowded, complex, less predictable and heterogeneous airspace; when operating procedures are inconsistent; when the controller is handling a less familiar sector; and under conditions of high workload or distraction. All of these factors, which contribute to the loss of situation awareness, will exert an even greater influence in a future environment of greater traffic loads, reduced separation minima, greater flexibility in routing, and other "free flight" scenarios. Usually, aircraft move routinely and predictably through the airspace, and so prediction is not too demanding. However, when multiple aircraft are free to move in four dimensions (three spatial and one time/airspeed) their positions at a future time is not nearly as predictable. In such conditions, controller's capabilities to monitor and remain aware of the airspace activity of

multiple aircraft will be severely taxed.. Such circumstances may be envisioned with the implementation of "free flight" concepts.

b. Decision making

[Decision making is vulnerable when information is incomplete, conflicting, or unreliable, or when goals conflict. Furthermore, vulnerability may be increased significantly whenever the controller is confronted with high work-load (e.g., large numbers of aircraft), novel situations, or tight time constraints. Time stress is a particularly important factor in decision making, because it forces the controller to choose among activities competing for attention. For example, the controller may choose to skip some low-priority activity, or process all of them but at a less complete level. The controller may defer some activities, placing them in a queue to be dealt with later. All of these strategies involve risk of error if the time available to revise and assess decisions is substantially reduced. Training and improved displays that promote effective decision making may help but only to the extent that time is available prior to taking action.]

c. Controller/pilot communication/coordination

(Also see section F.1.c. of this outline)

[Coordination, reflected in verbal communication between pilot and controller, will remain a critical component of air traffic control for the foreseeable future. A major cause of air traffic control incidents relates to breakdowns in communications and coordination between the pilot and controller. Communication effectiveness depends, among other things, on shared assumptions and shared situation awareness. These directly affect the ability of pilots and controllers to function effectively as a team. Uncertainty on the part of the controller or pilot and a reduction in the level of coordination can result from the lack of shared knowledge available to both members of the team. One way, perhaps, of facilitating teamwork is through a distributed management of air traffic control system between ground and air <u>with clearly defined areas of responsibility</u> and through shared displays and data link information..]

d. Controller/controller communications and coordination

[Controller "hand-offs" of aircraft from sector to sector and from one facility to another require a high level of communication and coordination. ATC facilities enter into procedural agreements with each other to assure this and automation is used to ease the process. Coordination is especially critical in the transition from en route airspace to terminal airspace, where aircraft sequencing for landing occurs. It is also critical in the transition from terminal airspace to the airport surface, where runway clearances must be assured.

Many air traffic control positions are staffed by two controllers who work together. This work design not only divides the task but also provides redundancy in the form of additional eyes and ears to

maintain situation awareness. However, under low traffic conditions supervisors will often elect to turn a team activity into an individual one. Although this practice does reduce staffing requirements it also removes the advantages of awareness redundancy. It is noteworthy that a substantial proportion of operational errors occurs during periods of low workload, when such combined activities are in effect.]

e. Controller response time

[ATC incidents occur in a real-time, dynamic, event-driven environment. Nevertheless, in today's environment, air traffic controllers normally have minutes or tens of minutes available to decide on actions (although there are exceptions). As a result, there normally is a long decision horizon and problem solving can extend over time with the possibility of incremental progress towards a solution and repeated inspection of progress and adjustment of that solution. Thus, a controller's responses are not just the result of a single decision. The monitoring of the results of the decision can provide additional diagnostic cues for adjusting future decisions and responses. However, any change in the airspace that would reduce the time available to the controller to formulate a plan or to take an action reduces the opportunity not only to generate an effective strategy, but also to revise understanding of the situation and to revise the response to an incident. Failure in making such revisions are sources of error in ATC problem solving.]

f. Controller workload

[Projected increases in air traffic and proposed reductions in aircraft separation minima may substantially increase cognitive demands on the controller. If safety is not to be compromised, controllers should not be subjected to sustained overload due to high traffic density or revised patterns of traffic what might lower their performance. While individual controllers may work most effectively at different workload levels, for each controller there are upper and lower workload thresholds outside of which the controllers' effectiveness diminishes. These limits may be increased with the introduction of new procedures and technologies such as more effective displays and decision aids.]

g. Interaction with displays/automation/decision aids

i. Displays

[The switch from hardwired displays to computer-based displays has, in general, not changed the way the display of information is conceived.. Too often, displays provide poor graphic images or alphanumeric data with little consideration for even basic human factors design. While technological power has generally advanced our ability to gather and manipulate data, it has rarely been used successfully to advance our ability to interpret this avalanche of data; i.e., to extract meaning from the display of data to support user goals/tasks. In short, we have to be careful that as we

increase the technological sophistication of computer-based ATC systems, we do not overload the information processing capacity of the controller. We have to be careful that as the demands of ATC performance increase, increases in data acquisition and manipulation do not overload memory or add new tasks that increase workload. We must always be mindful that a successful ATC display technology must help the controller extract relevant information under conditions of actual task performance (e.g., time pressure, risk, uncertainty, competing tasks) primarily by means of more integrated displays.]

ii. Automation

[Automation has the potential for improving ATC efficiency, handling increased traffic, and possibly enabling reduced separation minima while maintaining or improving safety. While automation has led to numerous benefits, including more efficient performance, elimination of some error types, and reduced controller workload in some cases, several potential costs have been noted. These include increased workload, increased monitoring demands, reduced situation awareness, unbalanced trust (mistrust and overtrust), new error forms, and loss of team cooperation. These costs, as well as the fact that perfectly reliable automation (or software) is not immediately possible, will influence the controller's choice to use or not use the automation.]

iii. Decision aids

[Advances in computer science and artificial intelligence are providing powerful new computational decision aids that greatly expand the potential to support cognitive activities in air traffic control, e.g., monitoring, problem detection, and planning. However, the introduction of new concepts of operation, including "free flight" and reduced separation minima, increases the likelihood for novel or unexpected situations to occur. Because automated decision aids are not very good problem solvers when situations depart from those the systems have been designed for, the automated aids are inherently "brittle". Breakdowns in performance can occur whenever attempts are made to automate the decision making process and assign the controller the passive role of following instructions. In short, one has to be very careful to ensure that decision aiding does not prevent the system from capitalizing on the insights and expertise of the controller. In addition, one has to insure that sufficient time budgets are available to a controller in the event a decision aid fails.. In order for decision aids to be useful they must be able to communicate with controllers in a form controllers can understand. Decision aids, if they are a mystery to controllers, can actually slow operations.]

    iv. Warnings/advisories
        1) Flight path prediction

[ATC automation that seeks to communicate a warning of an impending conflict directly to the controller requires that it compute an aircraft's future position using the aircraft's flight plan, performance, track, and wind data. However, the accuracy of flight path prediction is critically dependent on the accuracy and timeliness of the data, the variability of the winds, the certainty of pilots' intentions, as well as the effectiveness of detection and warning algorithms . Unreliability or unexpected variability in flight conditions limits the look-ahead time for accurate flight path prediction. If separation minima are reduced, an error in flight path prediction could result in a conflict with less time available to achieve successful resolution..]

        2) Conflict probe

[Unfortunately, many proposed conflict warning systems for the controller (e.g., conflict probe) are vulnerable to false alarms. The false alarm question is not trivial. As noted earlier, a comparable warning system on the flight deck, TCAS, suffered considerably in its early development from problems of excessive false alarm rates that resulted in mistrust and lack of pilot usage. At the same time, poorly designed controller warning and advisory systems will also foster disuse. What makes the false alarm problem more critical when separation minima are reduced and/or traffic density increases, is the necessity to insure that the reporting threshold for a conflict alert/warning is sufficiently lenient that few, if any, "true" conflicts are missed. However, if a warning system is designed to minimize "misses" then the problem of increased false alarms is immediately encountered. This is an intrinsic problem in developing an effective and sensitive conflict warning system.]

  h. Controller errors

[Controller errors are generally defined in terms of loss of separation. However, in considering risks associated with reduction in the separation minima, controller error must include a much wider range of inappropriate behaviors that result from mismatches between the cognitive demands placed on the controller and the resources available to solve those problems. To understand how the ATC environment can increase cognitive demands in terms of controller workload, memory, problem solving, decision making and the like is to understand how that environment contributes to controller error. Understanding the circumstances under which controller errors develop, from both a systems and a behavioral viewpoint, should make

*it possible to evaluate the consequences of ATC changes, like
reductions in separation minima on controller error and safety.]*

   i. Training

*[A critical question in designing effective training concerns how well
training in a simulator or on the job transfers to actual performance
on the job. On-the-job training, as typically practiced in ATC
facilities, trains controllers on task elements that are identical to those
on the job. Although the concept of on-the-job training has been well
established, there may be concerns about safety, job stress, and the
ability to provide the trainee with the full range of experiences in a
real world setting involving new operational concepts and
technologies. The stress of live performance and difficulty in
providing accurate, timely feedback in such an environment may make
on-the-job training less than ideal, suggesting the value of increased
use of simulation techniques.]*

   j. Corporate culture

*[The question that needs to be addressed when considering reductions
in separation minima is whether there are means available to prevent
the potential for increased risk. The conventional view within the
FAA is that all risks are manageable and that major
accidents/incidents are anomalies because people have not properly
done their jobs. The response, typically, is to preclude or mitigate
human error with more technology (e.g., automation). These
technological fixes are often cited as permitting increases in
efficiency or safety. TCAS, for example, is presently treated by ICAO
as a collision avoidance backup device, and not as a system enabling
reduced separation minima. However, there is a segment of the
aviation industry calling for just such a use of TCAS. In short, as
technologies improve, reduction in risk may not be fully realized
because the demand for greater flexibility and increased efficiency will
also increase. Also, since modern technical systems are made up of
thousands of parts, which interrelate in ways that are not always
possible to anticipate, it may be inevitable that some combinations of
minor failures will eventually result in a major accident or incident.]*

G. Environment

   1. Visibility

      a. Day/night/dusk/dawn

      b. Ceiling

      c. Sun position

      d. Clouds

      e. "Background" (i.e., against which pilot is to locate other aircraft)

   2. Adverse weather, storms

   3. Turbulence, wind shear

   4. Special problems (e.g., volcanic ash)

5. Wake vortex (may cause turbulence or engine problems for following
    aircraft at same or lower flight levels)

[This page intentionally blank.]

APPENDIX B

BIBLIOGRAPHY
(annotated)

[This page intentionally blank.]

A. Air Navigation Commission, "Review of the General Concept of
   Separation Panel, Sixth Meeting--Montreal, 28 November to 15 December
   1988--Report Volume 2, Montreal: ICAO, Doc 9536, December 1998.

   1. Topic: Mathematical models for collision risk

B. Air Navigation Commission, "Review of the General Concept of
   Separation Panel, Sixth Meeting--Montreal, 28 November to 15 December
   1988--Report, Volume 1," Montreal: ICAO, Doc 9536, RGCSP/6, Volume 1,
   1988

C. Anderson, D. and X. G. Lin, "A Collision Risk Model for a Crossing
   Track Separation Methodology

   1. Topic: Mathematical models for collision risk

D. Applied Techno-Management Systems, Inc. (ATMS), "Potential
   Operational Impacts of GPS with Advanced CNS and ATC Automation
   Technologies," Falls Church, VA: FAA Contract #DTA01-94-Y-00039,
   February 9, 1996

   1. The following sections of this report are readable,
      not-very-mathematical descriptions of the ways in which the
      geometry of direct routing will change collision risk. They
      should be read together, along with the Corrigenda.

      Section 4.3, "Free Flight and En-Route Air Safety," by Dr.
         Arnold Barnett, MIT (pp 109-138)
      Section 4.4, "Changes in the Geometry of Traffic Flow and their
         Consequences," by Dr. Anton Nagl, ATMS (pp 139-161) +
         Corrigenda

      Sections 4.1 and 4.2 (also by Dr. Anton Nagl) of the report are
      highly mathematical treatments of risk for parallel tracks and the
      impact of conflict detection and resolution algorithms on
      separation and risk.

E. Australian Airspace Classification System   Australian aviation
   http://www.aopa.com.au/aviation/airspac2.html

F. *Aviation Daily*, vol. 202, no. 6, p.44, 1972, "Decision Making in
   Free Flight," University of Minnesota Human Factors Research
   Laboratory, Flight Simulation Research Programs. new gif from jim of

FAAsim. Free Flight. The Federal Aviation Administration (FAA) has awarded a series...," http://hawk.psych.umn.edu/flight.html

1. Among other information, this site identified projects that the Human Factors Research Lab at the University of Minnesota was involved in. The one of interest to our efforts is a project being performed for the FAA:

Shared Decision Making in the National Airspace System: Define constraints on safe and effective decision making by commercial aircrew about routing and separation. Determine under what conditions Free Flight is likely to be safe.

G. AWOP, Fifteenth Meeting of the All Weather Operations Panel, ICAO, 26 September - 12 October 1994. Montreal, Quebec, Canada.

H. "B/CA's Viewing Area Grid System," *Business and Commercial Aviatio*n, vol. 37, no. 3 (1975), p.62-64.

1. The effectiveness of see-and-avoid concept is governed by cockpit viewing area. VAGS provides an analytical tool for objectively grading "cockpit visibility."

I. Baker, C.B., "Civil Airmiss Situation Analyzed in U.K. Study," CAA Paper no. 75001, 1975.

1. Findings in this study conducted by the CAA indicate that air misses can provide a practical monitor of ATC system effectiveness.

J. Bakker, G. J. and H.A.P. Blom, "Air Traffic Collision Risk Modelling," *Proc. 32nd IEEE Conf. on Decision and Control*, December 1993, pp. 1464-1469 (NLR report TP 93292 U).

1. Topic: Collision risk models

K. Ball, Dr. Celesta G., et. al., "Concepts for Future NAS Operations," McLean VA: MITRE Corp., Report No. MTR 950000107V3, September 1995

L. Ball, R.G., Lloyd, R.B. and Ord, G., "Computer Assisted Conflict Resolution in Air Traffic Control," 1974 Paper 17 presented at the 20th Symposium of the Guidance and Control Panel, in Cambridge, MA.

1. The controller needs computer assistance to display the trajectories the pilots intend to fly, warn the controller of

potential conflict, and suggest how such conflict might be
resolved.

M. Barnett, Arnold 1987, "Letters to the editor," *Interfaces*, Vol. 17,
No. 2, pp. 109-110.

N. Barrer, John N., "Concept For Establishing Improved Oceanic
Separation Standards Based On Equipment Certification," McLean, VA:
MITRE/CAASD, http://www.caasd.org/html_files/MP93W68/MP93W68.html

O. Barrer, John. "A Concept for Establishing Improved Oceanic
Separation Standards Based on Equipment Certification," McLean, VA:
MITRE/CAASD, MP93W68.

P. Barrer, John. "A Model for Assessing Collision Risk Associated with
Future Aircraft Navigation and Control," McLean, VA, The MITRE
Corporation, MTR-93W151, 1993.

Q. Baudry, H.G., "Proposed Partial and Interim Solution to Reduce
Vertical Separation Above FL290," ICAO Review or the General Concept
of Separation Panel (RGCSP), 1975, RGCSP-WP/54.

R. Bellantoni, Juan, F., "The Calculation of Aircraft Collision
Probabilities," Cambridge: US DOT Transportation Systems Center,
TSC-FAA-71-27, AD 744 722, N73-10046, 1971.

1. Statistical-probabilistic method applied to arbitrary flight paths
and spherical collision surfaces. The formulas are applied to
independent curved approaches to parallel runways.

S. Biemans, M.C.M. and J. Daams, "HOMEROS: Human Operator Modelling to
Evaluate Reliability, Organisation and Safety," RHEA/TH/WPR/6/1,
European Union DGVII, Contract number AI-95-SC.107, NLR, 1997.

T. Bilanin, A. J., M. E.Teske, and H. C. Curtiss, "Onboard Wake Vortex
Avoidance: Instrumentation to Quantify Vortex Wake Hazard," in J.N.
Hallock (Ed.), *Proceedings of Aircraft Wake Vortices Conference-
Vol.2. October 29-31, 1991*, Report No. DOT/FAA/SD-92/1.2, 1991.

U. Blake, N.A., et al., "Report of Task Force on Aircraft Separation
Assurance, Vol. 1, Executive Summary," Washington: FAA, Report No.
FAA-EM-78-19, Jan. 1979

V. Bliss, D. B., "Effects of Unsteady Forcing the Sinusoidal Instability
of Vortex Wakes," *Journal of Aircraft*, 19 (pp. 713-721). September

1982.

W. Blom, H.A.P. and G.J. Bakker, "A Macroscopic Assessment of the Target Safety Gain for Different En-Route Airspace Structures within SUATMS," NLR report CR 93364 L, 1993.

   1. Topic: Collision risk models

X. Blom, H.A.P., "The Layered Safety Concept, An Integrated Approach to the Design and Validation of Air Traffic Management Enhancements," NLR report TP 92046 L, 1993.

   1. Topic: Empirical or semi-empirical expressions

Y. Bosc, J. F. (ENAC) and G. Dean (EEC), "An Implementation of a Reactive Distributed Air Conflict Resolution System," ISADS 97 (International Symposium on Autonomous Decentralized Systems), April 1997

Z. Boswell, S. B., "Evaluation of the Capacity and Delay Benefits of Terminal Air Traffic Control Automation," Lexington, MA: Massachusetts Institute of Technology Lincoln Laboratory, ATC-192, 1993.

AA. Branstetter, J. R., Hastings, E. C., and Patterson, J. C. Jr. (1991), Flight Test to Determine Feasibility of a Proposed Airborne Wake Vortex Detection Concept, NASA Langley Research Center TM 102672, Federal Aviation Administration Report No. DOT/FAA/CT-TN 90/25.

AB. Briddon, A.E., E.A. Champie, and P.A. Marraine, *FAA Historical Fact Book A Chronology 1926-1971*, Washington: Federal Aviation Administration, 1974

AC. Brooker, P. and T. Ingham, "Target Levels of Safety for Controlled Airspace," CAA Paper 77002. Civil Aviation Authority, 1977.

   1. Topic: Risk Tolerability

AD. Brooker, P. and T. Ingraham, "Collision Risk in Air Traffic Systems: the Derivation of Longitudinal/Vertical Overlap Factor Pxz for Parallel Tracks," London: Civil Aviation Authority, April 1984, CAA Paper 77004.

   1. Update of paper listed above

AE. Brooker, P., "Collision Risk in Air Traffic Systems : The Derivation of the Longitudinal-Vertical Overlap Factor Pxz for Parallel Tracks," London: Civil Aviation Authority, 1977.

1. See 1984 version, below

AF. Brooker, Peter 1983, "Aircraft separation assurance: Systems design," *Journal of Navigation*, Vol. 36, No. 1 (1983), pp. 28-36.

AG. Brooker, Peter 1984, "Aircraft collision risk in the North Atlantic region," *Journal of the Operational Research Society*, Vol. 35, No. 8, 695-703.

AH. "Bulletin d'acquisitions des ouvrages, BibliothŠque de; Lyon Bron. Juin - Septembre 1996. Mise … jour Octobre 1996. Accidents. Bruit,...; --http://www.inrets.fr/html/doc/br_acq963.html

1. In French

AI. Burnham, D. C., and Hallock, J. N. (1982). Chicago Monostatic Acoustic Vortex Sensing System, Volume I: Wake Vortex Decay. Report No. DOT/FAA/RD-79-103, IV.

1. See 179 report, above.

AJ. Burnham, D. C., and Hallock, J. N., "Chicago Monostatic Acoustic Vortex Sensing System, Volume I: Data Collection and Reduction," Report No. DOT/FAA/RD-79-103, 1979.

1. See 1982 report, below

AK. Busch, Allen C., Brian Colamosca, and John R. Vander Veer, "Collision Risk and Economic Benefit Analysis of Composite Separation for the Central East Pacific Track System," FAA-EM-77-5.

AL. Busch, Allen C., Robert A. Rigolizzo and Brian F. Colamosca, "Analysis to Support Establishing Safety Criteria for the Study of Separation Standards--Draft Report," Atlantic City Airport, NJ: Federal Aviation Administration Technical Center, DOT/FAA/CT-TN, August 1986

AM. "CANAC Track Accuracy," [the Belgian Computer Assisted National Air Traffic Control Center (CANAC) system], http://www.caasd.org/html_files/MTR93W195/MTR93W195.html

1. The purpose of this study is to determine the collision risk associated with various levels of displayed separation in the Belgian airspace.

AN. Cassell, Rick, Alex Smith, and Roger Shepherd, "A Risk Assessment Model for Free Flight--Terminal Area Reduced Separation," *Proceedings of the 15th AIAA/IEEE Digital Avionics Systems Conference--Atlanta, October 1996*

AO. CEAS Conference. Confederation of European Aerospace Societies 10th European Aerospace Conference 20 - 21 October, Amsterdam, the Netherlands. Free Flight. http://www.nlr.nl/public/top/ceas/ceas.html

1. The theme of the Conference is centered around the technical and scientific problems associated with civil (and also military) safe and efficient free flight operations. Topics will include the following:

   Low visibility operations of aircraft
   En-route flight management
   Independent surveillance
   Collision avoidance systems
   Collision Risk Modelling
   Certification of procedures
   Recent experience

   If you intend to attend the Conference please complete the application form and send it to:

   The Free Flight Conference Secretariat
   c/o National Aerospace Laboratory NLR
   Attn. Mrs. A. Bredt
   P.O. Box 90502
   1006 BM Amsterdam
   The Netherlands
   tel. +31 20 511 3651 or +31 20 511 3244
   fax. +31 20 511 3210

AP. Coluris, George J. and Bjorn, Conrad, "Oceanic area system improvement study (OASIS), Vol. 1," FAA-EM-81-17-1, Menlo Park, CA: SRI International, 1981

AQ. Coote, M. A., G. W. Schraw, and R. W. Schwab, "Oceanic Requirements and Benefits Modeling for Automatic Dependent Surveillance (ADS),"

New York: John Wiley and Sons, Inc., *Air Traffic Control Quarterly*,
Vol. 1(1) (pp. 31-58), 1993

AR. Cotton, W.B., "Navigation Improvements -- To What End," *Proceedings
of the Annual Meeting, RTCA Nov. 1973*, 1973.

  1. The relationships between navigational accuracy and separation
     criteria is explored in view of FAA planning objectives.

AS. Craigie, J.H., D.D. Morrison, and I. Zipper, "Air Traffic Control
Surveillance Accuracy and Update Rate Study," TRW Systems Group,
NASA-CR_139043, N74-30094, 1973

  1. Air traffic control surveillance accuracy and update rate, and
     communications load related to tactical control of aircraft for
     conflict resolution.

AT. Croom, D. R., "The Development and Use of Spoilers as Vortex
Attenuators," *Wake Vortex Minimization Symposiu*m (pp. 339-368)
Washington D.C.: NASA SP-409, February 1976.

AU. Culhane, L.G. and B. Horowitz, "Conflict Alert and Intermittent
Positive Control," *AGARD Survey of Modern Air Traffic Control*,
AGARDograph 209, July 1975, N75-332047

  1. Presents analytical, simulation, and experimental results obtained
     in a study leading to the development of a ground-based collision
     avoidance system, including intermittent positive control for VFR
     aircraft conflicts.

AV. Datta, K. and R.M. Oliver, "A Model to Predict Mid-Air and Near
Mid-Air Collisions," *Journal of Forecasting*, v11. n3. (5/1/92)
p.207.

AW. Datta, K. and R.M. Oliver, "Predicting Risk of Near Midair Collisions
in Controlled Airspace," *Transportation Research, Part B,
Methodologica*, v25 no.4 (8/1/91) p.237.

AX. Datta, K. and R.M. Oliver, "Prediction of Mid-Air and Near-Mid-Air
Collisions: Final Report," Berkeley, CA: University of California,
Institute of Transportation Studies, 1988.

AY. Datta, Koushik and Robert M. Oliver, "Predicting Risk of NMACs in
Controlled Airspace," Berkeley, CA: University of California,
Institute of Transportation Studies, (UCB-ITS-RR-89-6) . 23p. $5.00.

AZ. Datta, Koushik and Robert M. Oliver, "Prediction of Mid-Air and Near-Mid-Air Collisions: Final Report," Berkeley, CA: University of California, Institute of Transportation Studies, (UCB-ITS-RR-88-16) 26p. $10.00.

BA. Datta, Koushik, "Predicting Risk Reduction of Aircraft Collision Avoidance Systems," Berkeley, CA: University of California, Institute of Transportation Studies, (UCB-ITS-DS-89-4) p. $50.00.

BB. David, H., "Conflict-Fee Direct Routings in European Airspace," EEC Report n?308, March 1997

BC. David, H., "Radical Revision of En-Route Air Traffic Control," EEC Report n?307, March 1997

BD. Davies, E. H., "Derivation of a Future TLS for Use in NAT Airspace," CS Report 9301, Civil Aviation Authority, August 1993.

  1. Topic: Risk Tolerability

BE. Davies, L. and A. Sharpe, "Review of the North Atlantic lateral collision risk model," *Air Traffic Control Quarterly*, John Wiley and Sons, Inc., SERIE - 1993 - VOL1 - N3 - P225-254 - E [BR-UTA0037, ?BR-UTA0038?],
  --http://www.orlab.faa.gov/VisitingResearcher/areas.htm

  1. This article presents a review of the method used to estimate lateral collision risk in North Atlantic minimum navigation performance specification airspace. The result is a risk assessment model in which each lateral navigation error is weighted according to the contribution it makes to the risk. This applies to all types of error and the magnitude of the weighting varies with the cause and size of the error. An analysis of the lateral collision risk for the year 1991 is performed using the model, showing the risk to be within the appropriate target level of safety. The North Atlantic Systems Planning Group have accepted this approach as the approved method of lateral risk estimation for the North Atlantic region.

BF. Dellon, F., "Navigational Performance Requirements for Reducing Route Centerline Spacing," Mitre Corp., June 1974, Mitre WP-10599

  1. Four approaches to what can be done to safely reduce the route center-line spacing requirement.

BG. Diamond, P.M., "The Potential of a System of Satellites as a Part of an Air Traffic Control System," AGARD CP-105 Air Traffic Control Systems, June 1972, pp. 20-1 to 20-17

   1. The ATC performance of satellite systems utilizing a data acquisition and communication role with the CONUS is discussed. Position determination, flow control, collision avoidance functions can be implemented using ground-based computer system.

BH. Dorfman, Dr. Gerald A., "Analysis of Aircrew Responses Affecting Simultaneous ILS Approaches, Volume 1: Executive Summary; Volume 2: Main Report" McLean, VA: MITRE CAASD, Report No. MTR 960000048, August 1996

BI. DOSLI Land Data Services: Land Data Services packages land information into a form suited precisely to the needs of its end users. The products and services cover an enormous... http://www.dosli.govt.nz/lds/ Includes some relevant material:

   1. Aeronautical computations.

   2. The safety of New Zealand's domestic and international air routes rest on the aeronautical computations carried out for the aviation industry by DOSLI. Services include calculating the positions of reporting points and navigational aids, calculations for airspace and flight clearances, provision of en-route track data and collision risk models.

BJ. Dunham, R. E., R. A. Steuver, and D.D. Vicroy, "The Challenges of Simulating Wake Vortex Encounters and Assessing Separation Criteria," NASA Langley Research Center. AIAA Atmospheric Flight Mechanics Conference. August 9-11. 1993, Monterey, CA.

BK. Dunlay, W. J. Jr., "Analytical Models of Perceived Air Traffic Control Conflicts," *Transportation Science,* Vol 9, 1975

BL. Dunlay, W., R. Horonjeff, and A. Kanafani, "Models for Estimating The Number of Conflicts Perceived by Air Traffic Controllers," California University, Inst. of Transportation and traffic Engineering, 1973, AD-A-023 533.

   1. Define and estimate the number of aircraft interactions where the controller perceives a potential loss of separation.

BM. El Arini, M. Bakri, et. al., "Development of an Error Budget for a Global Positioning System (GPS) Wide Area Augmentation System (WAAS)," http://www.caasd.org/html_files/MP94W10/MP94W10.html

BN. Endoh, Shinsuke, "Aircraft Collision Models," Cambridge: MIT Flight Transportation Library, 1982, FTL Report R82-2.

BO. Everdij, M.H.C., G.J. Bakker, P.J.G. Blanker and H.A.P. Blom, "Designing EATMS Iinherently Safe," TOSCA II WP 4, Eurocontrol, NLR, 1997.

BP. Everdij, M. H. C., G. J. Bakker and H. A. P. Blom, "Application of Collision Risk Tree Analysis to DCIA/CRDA Through Support of TOPAZ," NLR Report CR 96784 L, December 20, 1996

  1. Topic:General Risk Estimation Methodologies

BQ. Everdij, M. H. C., M. B. Klompsta, and H. A. P. Blom, "Development of Mathematical Techniques for ATM Safety Analysis," MUFTIS WPR 3.2 Final Report Part II, EU DGVII Contract number 8102-CT94-001, NLR 1995

  1. Topic:General Risk Estimation Methodologies

BR. Everdij, M.H.C., H.A.P. Blom and M.B. Klompstra, "Dynamically Coloured Petri Nets for Air Traffic Management Safety Purposes," *Proc. 8th IFAC Symposium on Transportation Systems, Creta, Greece June 1997* (preprint available from NRL).

  1. Topic: Collision risk models

BS. Everdij, M.H.C., M.B. Klompstra, H.A.P. Blom, and O.N. Fota, "Final Report on Safety Model, Part I: Evaluation of Hazard Analysis Techniques for Application to En-Route ATM," MUFTIS Work Package Report 3.2, The Netherlands: National Aerospace Laboratory, NLR report TR 96196 L, December 1995.

  1. Topic: General risk estimation methodologies

BT. Everdij, M.H.C., M.B. Klompstra, and H.A.P. Blom, "Final Report on Safety Model, Part II: Development of Mathematical Techniques for ATM Safety Analysis," MUFTIS Work Package Report 3.2, The Netherlands: National Aerospace Laboratory, NLR report TR 96197 L, March 1996.

1. Topic: Collision risk models

BU. FAA Advisory Circular No. AC 90-77, Sept. 1977

1. A program that alerts controllers to closures between two or more aircraft being incorporated in the ARTS III system.

BV. FAA Order 7110 68A, "Conflict Alert Function," March 1976

1. Establishes procedures and parameter values to be used within the conflict alert function of the NAS En Route Stage A System.

BW. FAA Satellite Program Office (AND-510), "FAA Satellite Navigation Program Master Plan," Washington: Federal Aviation Administration, Research and Acquisitions, August 31, l995

BX. FAA, NAFEC Letter Report No. NA-22-75-LR, Dec. 1975, "Conflict Prediction."

1. Describes test and evaluation of UNIVAC-developed conflict prediction program for ARTS-III.

BY. FAA, Office of Systems Engineering Management, "Summary of Near Term Engineering and Development Program Plans for Ground Based Separation Assurance," Report EM 73-7, AD 7651 560

BZ. Federal Aviation Administration, "FAA's Plan for Transition to GPS-Based Navigation and Landing Guidance," Washington: FAA, July 1966

CA. Federal Aviation Agency, *United States Manual of Radar Air Traffic Control Procedures, Revised First Edition,* Washington, May 1, 1958.

CB. Finnegan, P., "Flight Test Evaluation of AVOID II (Avionic Observation of Intruder Danger) Collision Avoidance System," Report No. NADC-76141, 1976, AD-A033 596, N77-22061

1. Comprehensive flight and laboratory evaluation of the AVOID II system, a proposed candidate for the national standard collision avoidance system. Tests included the ability to communicate accurate, correct and timely maneuver commands in simulated high traffic density.

CC. Flanagan, P.D. and K.E. Willis, "Frequency of Airspace Conflicts in the Mixed Terminal Environment," *Report of Department of*

Transportation Air Traffic Control Advisory Committee, Vol.2, Dec. 1969

CD. Flax, Bennett and Brian Colamosca, "RNP Values for Oceanic Separation," London: Review of the General Concept of Separation Panel (RGCSP) - Working Group A, Agenda Item 1: "Required Navigation Performance Working Paper," September 17-18, 1992 (RGCSP-WG/A-WP/11, 28/08/92)

CE. Foot, P.B., "A Review of the Results of a Trial Hazard Analysis of Airspace Sectors 24 and 26S," Civil Aviation Authority, CS Report 9427, 1994.

CF. Fota, O.N., "Etude de Faisabilitit, d'Analyse Globale de la S,curit, d'un CCR … l'aide de l'EPS (Evaluation Probabiliste de la S,curit,)," Centre d'•tudes de la Navigation A,rienne, Rapport CENA/R93-022, 1993.

CG. Friedman, M. F., "Decision Analysis and Optimality in Air Traffic Control Conflict Resolution: II Optimal Heading (Vectoring) Control in a Linear Planar Configuration," *Transportation Research B,* vol. 25B, No. 1, 1991: 39-53

  1. Topic: Mathematical models for collision risk

CH. Gaton, V.A.and M. Harmatz, "Computational Estimate of the Separation effect," *Journal of Aircraft*, v32. no. 6 (11/1/95) p.1322.

CI. Geisinger, Kenneth, "Analytic Blunder Risk Model (ABRM)," Washington: Federal Aviation Administration, January 1995

CJ. Geisinger, Kenneth E., "Airspace Conflict Equations," *Transportation Sciences,* 19:2, May 1985, pp. 139-153

  1. Topic: Mathematical models for collision risk

CK. Gely, A., "Air Collision Prevention," Paris: *Navigation,* vol. 20, July 1972 (In FRENCH)

  1. A review of the causes and prevention of air collisions, including rules of the road, visual detection, and proposed airborne and ground-based collision avoidance systems. Some recent collisions are analyzed.

CL. Gerard, R., Research area: Aviation Collision Risk, Department of

Actuarial Science and Statistics, City University, London, U.K.
[Research interests of Staff:
http://web.city.ac.uk/actstat/dept/research.html]

1. Dr R. Gerrard is developing statistical methodology for monitoring
the risk of fatal collision on North Atlantic aviation routes as
well as assessing the risk profile for locations in the vicinity
of major airports.

CM. Gerhardt, Christine M. (under vthe direction of E. A. Elsayed)
"Modeling of the Air Traffic Activity and Separation Minima Over the
North Atlantic Ocean," New Brunswick, NJ: Rutgers Univ., Master's
Thesis, May 1997

CN. Gifford, J. L. and P. Sinha, "Airport Congestion and Near-Midair
Collisions," *Transportation Res*, 25A, 1991

1. Topic: Empirical or semi-empirical expressions

CO. Gladstone, C. X. and M.S. Friedman, "Simultaneous Instrument Approach
Model (SIAM) Version 2," McLean VA: MITRE/CAASD, MTR 95W0000117,
1995.

CP. Gosling, Geoffrey D. (Editor), "New Technology and the Aviation
System, Proceedings of a Conference Held in Los Angeles, California,
November 16-18, 1988," Berkeley, CA: University of California,
Institute of Transportation Studies, (UCB-ITS-P-89-1) 259p. $35.00.

CQ. Graham W., "Terminal Air Traffic Flow and Collision Exposure,"
Proceedings of the IEEE, 58, March 1970

1. Topic: Empirical or semi-empirical expressions

CR. Graham, W. and R. H. Orr, "Terminal Air Traffic Model with Near
Midair Collision and Midair Collision Comparison," *Report of
Department of Transportation Air Traffic Control Advisory Committee,*
Vol.2, Dec. 1969

CS. Graham, W. and V. Mangulis, "Results of an Aircraft Visibility
Questionnaire Concerned with the Estimated Benefits of Airborne
Proximity Warning Indicator Systems," Control Data Corp., FAA Report
RD 75-46, 1975, AD-A009 884, N75-20961

1. Results of 3,000 questionnaires about pilot preferences on PWI
displays. Contains estimates time required to for pilot to avoid

a pending collision.

CT. Graham, W., "See and Avoid/Cockpit Visibility," (Technical note), Centerpoint, NY: Questek, Inc., October 1989, 24 pgs. (ADNUMBER: ADA214214; MONITORACRONYM: DOT/FAA/CT; MONITORSERIES: TN/89/18.)

   1. This study was conducted in response to the Federal Aviation Administration's (FAA) Office of Aviation Safety and the recommendations of the Interagency Near Midair Collision (NMAC) Working Group, dated July 21, 1986, which suggested a review of see and avoid effectiveness, conspicuity enhancement, and their relationship to cockpit visibility. This report summarizes the salient facts in these areas, based on a review of the literature, and assesses the potential for significant reduction of collision risk. The study was conducted by Walton Graham, Questek, Incorporated, who was previously involved in numerous FAA see and avoid, pilot warning instrument/ collision risk studies and analyses of the near midair collision data. Keywords: See and avoid, Conspicuity enhancement, Cockpit visibility.

CU. Greene, G. C., "An Approximate Model of Vortex Decay in the Atmosphere," *Journal of Aircraft,* Vol. 23, No. 7. July 1986, pp. 566-573).

CV. Greenwood, J., "Procedures for Assessing Radar Separation Standards," Civil Aviation Authority, CS Report 9334, August 1993.

   1. Topic: Empirical or semi-empirical expressions

CW. Haines, A.L., B. M. Horowitz, and A.P. Smith, "A General Model for Separation Standard Assessment," McLean, VA: Mitre Corp., Mitre Tech. Report MTR-6909, 1975

   1. Concepts of a general model for assessment of separation standards in an ATC system.

CX. Hallock, J. N., and W.R. Eberle, Editors, "Aircraft Wake Vortices: A State-of-the-Art Review of the United States R and D Program," U.S. DOT Transportation Systems Center, Lockheed Missiles and Space Co. FAA-RD-77-23, February 1977.

CY. Hallock, J. N., B. P. Winston, T. S. Sullivan, and D. C. Burnham, "TSC Wake Vortex Data Base and Applications," *Proceedings of the Aircraft Wake Vortices Conference, March 15-17, 1977*, Cambridge, MA:

U.S. DOT Transportation Systems Center, 1977.

CZ. Hallock, J. N., Editor, "Proceedings of the Aircraft Wake Vortices
   Conference October 29-31, 1991," Washington: 1992.

DA. Hanson, J.R., "Visual Aspects," *Flight Safety Facts and Analysis,*
   vol.3, no. 11, 1972

   1. Aspects of visual collision avoidance pointing out that the moving
      target attracts attention, but an apparently stationary target is
      the ONLY one where a midair collision results.

DB. Harris, J.L., "Visual Aspects of Air Collision," *Visual Search,*
   1970, symposium conducted by the National Academy of Sciences,
   National Research Council, Division of Behavior Sciences.

   1. A technique of calculation applicable to the air collision problem
      showing that a clear understanding of the pilot's cockpit workload
      is necessary prerequisite.

DC. Hassan, A.A. and L.N. Sankar, "Separation Control Using Moving
   Surface Effects: A Numerical Simulation," *Journal of Aircraft,* v29
   no. 1 (11/1/92) p.131.

DD. Hazard Analysis of an En-Route Sector," Civil Aviation Authority, RMC
   Report R93-81(S) October 1993 [Volume 1 (Main Report); Volume 2]

   1. Topic: General Risk Estimation Methodologies

DE. Hegarty, Chris, Pete Wroblewski and Kelly Markin, "An Assessment of
   the Ability of Augmented GPS to Provide Sole Means Navigation:
   Interim Report," McLean, VA: MITRE CAASD, Report No. WN 95W0000254,
   May 5, 1996

DF. Herbert, J.W., "Cockpit Traffic Display," *Flight,* vol.61, no.5,
   1972

   1. The ATSD (Airborne Traffic Situation Display) being tested by the
      M.I.T. Lincoln Lab. makes it possible for the pilot to see what's
      going on and maneuver accordingly without confusion from
      ground-based controllers.

DG. Hinson, R.M. Jr., "A Collision Avoidance Warning Criterion for
   Maneuvering Aircraft," PH.D Thesis, Georgia Inst. of Technology,
   1972, N73-21915, Univ. Microfilm order no. 72-26306

1. A warning criteria for areas where traffic densities are high and aircraft maneuvers occur frequently, based on the probability of a collision.

DH. Hinton, D. A. (1995), "Aircraft Vortex Spacing System (AVOSS) Conceptual Design," Hampton, VA: NASA Langley Research Center, TM 110184.

DI. Hockaday, Stephen L. N., "Air Traffic Control Evaluation Model," (UCB-ITS-TD-86-3) 8p. $15.00.

DJ. Hockaday, Stephen L. N., "Development of Alternative Air Traffic Control Strategies," Berkeley, CA: University of California, Institute of Transportation Studies, (UCB-ITS-WP-86-12) 38p. $10.00.

DK. Hollister, K. (1992), "Blunder Risk Model, Version 1.0," Lexington, MA: Massachusetts Institute of Technology Lincoln Laboratory, ATC Project Memo: 42PM-PRM-0011.

DL. Hollnagel, E., *Human Reliability Analysis Context and Control,* Academic Press, London, 1993.

DM. Holt, J.M., "Safe Separation in Controlled Flight," *Navigation,* vol. 21, no.1, 1974.

1. Consequences of the point of view that separations must be adequate for ATC to provide protection against blunders or failures aboard the aircraft.

DN. Hopkins, V.D., "Human Factors Problems in Conflict Detection and Avoidance," AGARD CP-105 Air Traffic Control Systems, Paper presented at the Guidance and Control panel of AGARD, Edinburgh, Scotland, 1972, Paper 25-1 to 25-6

1. Conflict detection and avoidance poses different problems, depending on large differences in information, procedures, and facilities. The controller's responses depends on the confidence he/she has in the data presented.

DO. Horton, W.F., Jr, "Conflict Prediction Theory for Automated IFR Traffic Control," Mitre Corp., Mitre Working Paper WP-10911, 1975

1. Conflict prediction algorithm based upon flight plan data and a description of the airspace region in which the conflicts may

occur., as part of a computer program to generate conflict-free
clearances for all IFR aircraft.

DP. Hsu, D.E., "Analysis of Aircraft Collision Risk on Intersecting Track
Systems with Application to Air Traffic Control," Princeton Univ.,
July 1977

1. Topic: Collision risk models

DQ. Hsu, D.A., "The Evaluation of Aircraft Collision Probabilities at
Intersecting Air Routes," *Journal of Navigation,* Vol. 34, No. 1,
January 1981

1. Topic: Collision risk models

DR. ICAO (International Civil Aviation Organization), "Manual on Required
Navigation Performance (RNP)," 1994, Doc. 9613-AN/937, Montreal,
Quebec, Canada.

DS. ICAO (International Civil Aviation Organization), "Air Traffic
Services Planning Manual," 1984, Doc 9426-AN/924. Amendments dated
15 Aug 85, 11 Sep 85, 3 Nov 88, Montreal, Quebec, Canada.

DT. ICAO (International Civil Aviation Organization), "Methodology for
the Derivation of Separation Minima Applied to the Spacing Between
Parallel Tracks in ATS Route Structures, 2nd Edition," Montreal: ICAO
circular; 120-AN/89/2, 1976 (267 pp +).

DU. ICAO (International Civil Aviation Organization), "Report of the
Sixth Meeting of the Review of the General Concept of Separation
Panel," November-December, 1988, Montreal, Quebec, Canada

DV. ICAO, "Manual on Airspace Planning Methodology for the Determination
of Separation Minima, Version 3.0," RGCSP/9-WP/25, 26 Feb. 1996.

DW. ICAO, "Manual on Airspace Planning Methodology for the Determination
of Separation Minima," RGCSP 9, May 1996, ICAO Doc XXXX - *To be
published.*

1. Topic:General Risk Estimation Methodologies

DX. ICAO, "Manual on Implementation of 300m (1000ft) Vertical Separation
Minimum Between FL290 and FL410 Inclusive," ICAO Doc 9574-AN/934,
First Edition, 1992.

1. Topic: Mathematical models for collision risk

DY. ICAO, "Manual on the Use of the Collision Risk Model (CRM) for ILS
   Operations," ICAO document # DOC 9274-AN/904. [ICAO, (Attention
   Distribution Officer) P. O. Box 400, Place de l'Aviation
   Internationale 1000 Sherbrooke Street West, Montreal, Quebec, Canada
   H3A 2R2

DZ. ITS Publications, ITS Publications: Title Index.
   http://www.its.berkeley.edu/pubs/titles.html

   1. This is a University of California at Berkeley site that records
      the titles of some of their transportation program reports. Some
      of the FAA old-timers may remember a formal agreement the FAA had
      with this program (FAA sent candidates and money, UC sent back
      advanced-degree graduates).

EA. James, M.K. "The Timing of Collision Avoidance Manoevres:
   Descriptive Mathematical Models," *The Journal of Navigation,* v. 47,
   no. 2, 5/1/94.

EB. Jeng, Chawn-Yaw, "Routing Strategies for an Idealized Airline
   Network," Berkeley, CA: University of California, Institute of
   Transportation Studies, (UCB-ITS-DS-87-3) p. $50.00.

EC. Johnson, D.B., "Impact of New Separation Standards," *Proceedings of
   the Eighteenth Annual Meeting,* Air Traffic Control Association,
   1973.

   1. Significance of new separation standards from the pilot's point of
      view. Attention given to terminal control area, separation
      standards for heavy jets, and holding patterns.

ED. Joseph, Mark, "Air Traffic Services Safety and Interoperability
   Requirements Position Paper," MITRE CAASD and RTCA SC-189/EUROCAE
   WG-53, June 6, 1997.

EE. Joyce, K., A. Schust, B. Colamosca, R. Rigolizzo and W. Smoot,
   "Summary Report of United States Studies on 1,000-Foot Vertical
   Separation Above Flight Level 290," Washington: Advanced System
   Design, FAA, July 1988

EF. Kelly, R.J. and J. M. Davis, "Required Navigation Performance (RNP)
   for Precision Approach and Landing with GNSS Application,"
   NAVIGATION: Journal of the Institute of Navigation, 41:1, Spring

1994

EG. King, M. L., "Radar Separation in the Terminal Area," informal internal memorandum, ARD-104, Washington: Federal Aviation Administration, November 14, 1974.

EH. Klein, Gary L., et. al., "Concepts for Future NAS Operations," McLean, VA: MITRE CAASD, Report No. MTR 95W0000107VI, September 1995

EI. Komons, Nick A., *Bonfires to Beacons, Federal Policy Under the Air Commerce Act 1926-1938,* Washington: DOT, FAA, 1978.

EJ. Knecht, William R., "Developing Probabilistic Metric of Midair Collision Risk," TRB 76th Annual Meeting. [Session Details: Sunday January 12. Monday January 13. Tuesday January 14. Wednesday January 15. Thursday January 16; http://www.nas.edu/trb/meeting/sess97d.html]

EK. Koushik Datta and Robert M. Oliver, "Predicting risk of NMACs in controlled airspace," Berkeley, CA: University of California, Institute of Transportation Studies, 1989.

EL. Kuchar, James, "Alerting Logic Development for Free Flight," Sponsored by the National Aeronautics and Space Administration Ames Research Center.

   1. Development and evaluation of a prototype alerting system for collision avoidance in a free flight environment. The system is based on probabilistic models of sensors, dynamics and humans and is being evaluated in simulation studies.

EM. Kuchar, James, "Parallel Approach Alerting Systems"
   1. A project investigating advanced airborne alerting systems for collision avoidance during approach to closely-spaced parallel runways. A prototype system has been developed and evaluated in several simulation studies. Work continues toward improving performance and identifying issues requiring more study. Sponsored by the National Aeronautics and Space Administration Langley Research Center.

EN. Kullstam, P. A., "Parallel Runway Spacing," *Journal of the Institute of Navigation,* Vol. 19, No.1. Spring 1972.

EO. Köpp, F., "Doppler Lidar Investigation of Wake Vortex Transport Between Closely Spaced Parallel Runways," *AIAA Journal,* Vol. 82,

No. 4, April 1994.

EP. Langley Technical Report Server:
http://www.kari.re.kr/www_home/ltrs/abs.html
http://techreports.larc.nasa.gov/ltrs/abs.html

1. This NASA Langley's electronic catalog of research papers and
reports. I suspect it is not complete. Regardless, most of the
work reviewed pertains to aircraft structures and airfoil-airframe
physics. A few reports are related to human factors (usually the
purview of NASA-Ames), software reliability and tests involving
the famous Langley wind tunnel. NASA Langley used to have a nest
of researchers interested in aircraft guidance and control (with a
little navigation thrown in). I was surprised not to see any work
related to those areas. Perhaps they have been reorganized to
other sites or out of existence.

EQ. Law M., "A Study of Systematic Distortions Observed in Monopulse SSR
Data from Clee Hill Radar," Civil Aviation Authority, DORA Report
9125, June 1991.

1. Topic: Empirical or semi-empirical expressions

ER. Lind, A. T., "Two Simulation Studies of Precision Runway Monitoring
of Independent Approaches to Closely Spaced Parallel Runways,"
Lexington, MA: MIT/Lincoln Laboratory, Project Report ATC 190, 1993.

ES. Livingston, Dale A., A. Strazzieri, and D. Baart, "Application of
Composite Separation to the North Pacific Track System," Atlantic
City Airport: Federal Aviation Administration Technical Center, July
1984, FAA Technical Note, FAA/CT-TN 83/84.

ET. Lloyd, D.E. and P.P. Scott, "Application of Monte Carlo Methods to
Estimation of Collision Risks Associated with ATC Separation
Standards," Royal Aircraft Establishment Report no. RAE-TR-73104,
1973, AD 773 313, N74-19238

1. Risk of collision between two aircraft nominally separated by ATC
procedures depends on several quantities which cannot be
determined exactly. This report uses Monte Carlo methods. As an
example, the report considers the proposed 90 mile lateral
separation for North Atlantic jet aircraft.

EU. Loiderman, E., "A Planning Tool for Predicting Enroute ATC Conflicts
and Designing ATC Sectors," Cambridge: MIT Flight Transportation

Laboratory, Sept. 1986, FTL Report R-86-14.

EV. Machol, R. E. and R. B. Rovinsky , "Some More Challenging Aviation OR
    Problems," Detroit: ORSA/TIMS Conference, Oct. 24, 1994

   1. Challenging problems facing the government sector include:
    collision-risk models; cooperative airline/air traffic control
    decision-making; R&D portfolio analysis; capital facilities
    investment analysis and how to redesign the airspace to take full
    advantage of new satellite and avionics technologies. We outline
    each problem and describe current and future plans.

   2. A general discussion of the title subject including a bit about
    past collision risk modeling and separation standards, airspace
    design, delays, and investment. Probably nothing new to anyone on
    the team.

EW. Machol, Robert E. 1975, "An Aircraft Collision Model," *Management
    Science,* Vol. 21, No. 10, (June 1975) pp. 1089-1101.

EX. Machol, Robert E., "Thirty Years of Modeling Midair Collisions,"
    Interfaces, Institute for Operations Research and the Management
    Sciences, 25:5 September-October 1995 (151-172)

   1. For 30 years, operations researchers have developed mathematical
    models of processes leading to possible collisions of aircraft
    flying in proximity to one another in order to estimate the risk
    of collision. These "collision risk models" were applied in the
    1960s to determine safe separation standards between pairs of
    co-altitude aircraft on parallel courses over the North Atlantic
    Ocean. The models have been and are being continually refined and
    improved. They have been applied to different geographic regions
    (for example, the Pacific Ocean and domestic airspace), to
    different flight regimes (for example, high-altitude cruise and
    landing on closely spaced runways), and to different types of
    separation (vertical and longitudinal as well as lateral).

EY. Marks, Brian L., "Air traffic [Control] Separation Standards and
    Collision Risk," Farnborough, United Kingdom, Royal Aircraft
    Establishment, RAE Tech Note No. Math 91, 1963.

   1. Said by some to be the work from which the Reich model was
    derived.

EZ. May, G. T. A., "A Method for Predicting the Number of Near Mid-Air

Collisions in a Defined Airspace," London: *J Inst Navigation,* April 1971.

   1. Note some of the expressions in this reference need correcting.

   2. Topic: Mathematical models for collision risk

FA. Mclaughlin, Michael F. and Andrew D., "Safety Study of TCAS II for Logic Version 6.04," McLean, VA: Mitre Corp., July 1992, 99 pgs. (ADNUMBER: ADA256364.)

   1. A new System Safety Study of Traffic Alert and Collision Avoidance System II (TCAS II) was performed to compare the safety of logic version 6.04 with the present version 6.0. The study uses a considerable body of encounter data extracted from Automated Radar Terminal System (ARTS) ground-based radar data at eight U.S. sites. Encounter geometries are modeled using the statistics of the observed data. The performance of TCAS logic is simulated using both complete logic versions. The perceived separation statistics are combined with altimetry error models to calculate risk for each encounter geometry. These results are combined in the proportions of encounter geometries found in the airspace at each site. Using a fault tree for the Critical Near Midair Collision event, the Risk Ratio is calculated for each logic version relative to the risk of not using TCAS. This result is discussed in the context of the improved compatibility of the newer logic with respect to the Air Traffic Control (ATC) system, which would increase overall safety.

FB. Meskhat, Leila and Dyana Mugijanto, "Midair Collision Risk Model," Washington: The George Washington University, School of Engineering and Applied Science, Department of Operations Research, Problems in Operations Research #OR 291, May 1997

FC. Millhollen, A., "Summary of Air-to-Air Visual Detection Data," Control Data Corp., FAA-RD-73-40, 1973

   1. An analysis of tests conducted to determine the ability of pilots to visually identify aircraft in time to take evasive action. Specific cases of near collisions are cited to show feasibility of collision avoidance by visual perception.

FD. Millhollon, A., J. Lyons, and W. Graham, "Air-to-Air Visual Detection Data," Interim Report, Control Data Corp., FAA-RD-73-40, 1973.

1. Test conducted to determine ability of pilots to visually detect other aircraft in the air. It was concluded that there is a high likelihood of seeing and avoiding an intruder aircraft under VFR conditions if the pilot is given accurate information on the location of the aircraft.

FE. Moek, G. and D. Harrison, "European Studies to Investigate the Feasibility of Using 1000 ft Vertical Separation Minima Above FL290, Part II, Precision Radar Data Analysis and Collision Risk Assessment," *Journal of Navigation,* Vol.45, no 1, 1992, pp 91-106.

1. Topic: Collision risk models

FF. Moek, G., J.M. ten Have, D. Harrison and M.E. Cox, "European Studies to Investigate the Feasibility of Using 1000 ft Vertical Separation Minima above FL290, Part III, Further Results and Overall Conclusion," *Journal of Navigation,* Vol.46, no 2, May 1993, pp 245-261.

1. Topic: Collision risk models

FG. Moek, G., J.P. Beaujard, C. Kelly, J. Mann, L. Clarke, D. Marsh, H. Blom, and M. Klompstra, "GENeric Overall Validation for ATM, WP3 Report: Methods and Techniques," EU-DGVII, Contract number AI-95-SC.112, 1997

1. Topic: Risk Tolerability

FH. Moek, G., M.A. Piers, M.P. Loog, M.K.H. Giesberts, M.J.H. Couwenberg and M.C.J. Smeets, "The Development of a Method for the Analysis of Societal and Individual Risk due to Aircraft Accidents in the Vicinity of Airports," NLR report CR 93372 L, 1993.

1. Topic: Risk Tolerability

FI. NASA Ames: Aviation Operations Branch, Mission Statement Research Programs, Publications Related Sites. Contact Information, Webmaster: Greg Pisanich. http://olias.arc.nasa.gov/

1. The NASA work includes a body of excellent human factors studies. Their flightdeck management studies would seem to have direct applicability to controller teams. To my best understanding of the reports I have read, and the bibliographies I have browsed -- they have not reformulated any of their work in terms of risk

analysis. Their models of decision-making and flight crew performance would have to be scoured for opportunities to quantify "foul-ups per fortnight" or whatever else we might want to measure.

FJ. NASA Safety Study - NEWS RELEASE: June 30, 1995 CONTACT: info@rannoch.com.; New Study will Determine Relationship Between Safety Risk, Aircraft Separation Standards,; and...; --http://206.205.144.3/pr63095.html

FK. NAT, "Guidance Material on the Implementation of a 300m (1000ft) Vertical Separation Minimum in the Minimum Navigation Performance Specifications Airspace of the NAT Region," NAT Doc 002, First Edition, 1994.

    1. Topic: Mathematical models for collision risk

FL. NAT, "Risk Assessment and System Monitoring for the Verification and Operation of a 300m (1000ft) Vertical Separation Minimum in the Minimum Navigation Performance Specifications Airspace of the North Atlantic Region," Supplement to NAT Doc 002, Draft Version 2.1, August 1996.

    1. Topic: Mathematical models for collision risk

FM. "NTSB Blames Control System in Midair Collision," *Aviation Daily,* vol. 202, no. 6, p.44, 1972.

    1. Probable cause in the Jan. 9, 1971 collision near Newark, N.J. airport involving an American B707 and a Cessna 150 was "inability of the crews of both aircraft to see and avoid each other while operating in a system which permits VFR aircraft to operate up to 3,000 feet on random headings and altitudes in a congested area under conditions of reduced visibility. " Other causal factors "were the deviation of the air carrier airplane from its clearance altitude and the conducting of student flight training in a congested control area under marginal flight visibility conditions."

FN. Ozmore, Richard E. and Sherri L. Morrow, "Evaluation of Dual Simultaneous Instrument Landing System Approaches to Runways Spaced 3000 Feet Apart with One Localizer Offset Using a Precision Runway Monitor System," Atlantic City International Airport: FAA William J. Hughes Technical Center, Report No. DOT/FAA/CT-96/2, September 1996

FO. Paielli, Russell A. and Heintz Erzberger, "Aircraft Trajectory Conflict Probability Estimation," Moffett Field, CA: NASA Ames Research Center, Jan. 22, 1996

   1. The paper describes an algorithm for estimating the probability of a conflict between two aircraft, "... given a predicted pair of trajectories and their levels of uncertainty." ["A conflict is defined here as having two or more aircraft come within some minimum allowed separation distance from each other."]

   The trajectory prediction errors (along-track, cross-track, vertical) are modeled as normally distributed, independent random variables. For computational efficiency, transformations of coordinates are made and the two distributions [i.e., prediction error covariance matrices] are combined, in effect assuming one aircraft has no predicted position error, and assigning all of the error to the other aircraft. Numerical integration is then used, employing a 3-dimensional grid, with the probability of an aircraft being within a grid element approximated by the probability density at the center of the element and the volume of the element. Inputs to the computation are the path crossing angle, the predicted minimum separation, and the predicted time of minimum separation. Numerical and graphical examples are given.

   COMMENTS:

   Is the normality assumption reasonable? The authors quote a reference for this assumption, but the papers I've seen usually assume a double exponential or double-double exponential distribution for horizontal errors, or at least for cross-track errors.

   Is the assumption of independent prediction errors justified, as potentially conflicting aircraft would both be affected by "the same" winds?

FP. Parker, I. G., "A Review of Work on Deriving a Target Level of Safety (TLS) for En-route Collision Risk," RGCSP WG/A, WP/8, Brussels, May 1995.

   1. Topic: Risk Tolerability, Target Levels of Safety

   2. Very readable

FQ. Peterkofsky, Roy I., "Knowledge-Based Relative Prioritization of

Aircraft for Air Traffic Flow Control," Berkeley, CA: University of California, Institute of Transportation Studies, (UCB-ITS-WP-86-4) 46p. $10.00.

FR. Polhemus, N.W. and D. Livingston, "Characterizing Cross-Track Error Distributions for Continental Jet Routes," *Journal of Navigation,* Vol.34, No.1, 1981

FS. Polhemus, N.W., "Collision Risk Modeling for Continental Jet Routes," Unpublished

FT. Pool, A, "Historical Development of Collision Risk Models for En-Route Air Traffic"

1. Topic: Mathematical models for collision risk

FU. Popp, (Captain) Peter T., USAF, "The Physical Limitations of the 'See and Avoid' Concept for Separation of Air Traffic," *ISASI Forum,* September 1995

1. This paper concludes that the use of "see and avoid" in preventing en route midair collisions is of extremely limited usefulness. This conclusion is reached based on compelling arguments and research about the limitations of normal human vision. These limitations include the following:

The very narrow area in which the eye has its best visual acuity - only about 2 degrees of the total visual field.

The scanning motion of the eye when looking for something., which results in large gaps in the visual field when scanning for distant objects.

Empty-field myopia, the natural tendency of the eye to focus at a distance of 12" to 36" when scanning a clear sky.

The fact "... that an object must cover approximately 12 minutes of arc to be reasonably recognizable as another aircraft (NTSB, 1993)." Furthermore, this limitation is when the eye is directly looking at the object. Objects outside the 2 degree area of best vision are less likely to be recognized.

A simulator study concludes that the point where avoiding a midair collision becomes pure chance is approximately 160 knots closing

speed. [Naturally, this depends on the size of the intruding
aircraft]

[This study does not take into account other visual difficulties,
including the difficulty a pilot may have in determining if a
distant, intruding aircraft is at, above, or below his/her
aircraft's altitude and in estimating both the distance of an
intruding aircraft and its distance at closest approach.]

FV. Porter, David B., "A Numerical Study of Airplanes Flying in
Proximity," (Master's thesis), MONTEREY CA: NAVAL POSTGRADUATE
SCHOOL, September 1993, 140 pages. (ADNUMBER: ADA273373.)

1. During an emergency such as an unsafe landing gear indication, a
second aircraft is often used to perform an airborne visual
inspection of the landing gear. The chase airplane may be quite
dissimilar in size and wing loading and consequently experience
unexpected aerodynamic forces and moments caused by the other
airplane. A numerical study of the inherent danger involved with
the aerodynamic interaction of aircraft flying in proximity was
made using the low-order panel code PMARC (Panel Method Ames
Research Center). PMARC validation was made by comparing wind
tunnel and analytically derived stability data for T-34 and F-14
models with PMARC results. A T-34 was then placed at various
distances underneath an F-14 to determine changes in lift and
pitching moments on the T-34. Color illustrations of pressure
coefficients were used to highlight the changes in aerodynamic
forces and moments as vertical separation between the two aircraft
was decreased. PMARC showed that 4.5 deg. of elevator trim change
were required as a T-34 approached to within its semispan of an F-
14. Formation flying, Panel method, Stability and control

FW. Precision Runway Monitor Program Office, "Precision Runway Monitor
Demonstration Report," Washington: FAA Research and Development
Service, Report No. DOT/FAA/RD-91/5, February 1991

FX. Prinzo, O. V., "An Analysis of Approach Control/Pilot Voice
Communications," Oklahoma City: FAA Civil Aeromedical Institute,
October 1996, 40 pgs. (ADNUMBER: ADA317528.)

1. This report consists of an analysis of air traffic control and
pilot voice communications that occurred at 3 terminal air traffic
control facilities (TRACONs). Each transmission was parsed into
communication elements. Each communication element was assigned to
a speech act category (e.g., address, instruction, request,

advisory) and aviation topic (e.g., heading, altitude, speed, readback) and evaluated using the aviation topic-speech act taxonomy (ATSAT, Prinzo, et al., 1995). A total of 12,200 communication elements in 4,500 transmissions make up the database. Communication elements appeared most frequently in the address and instruction speech act categories. Of the 2,500 controller communication elements, 40% contained at least 1 communication error. The number and types of communication errors (message content and delivery technique) located within each speech act category were determined and separate communication error analyses are reported for pilots and controllers by TRACON facility. Of the 5,900 pilot communication elements, 59% contained at least 1 communication error. More than 50% of controllers and pilots communication errors occurred in the instruction speech act category. Generally, controllers omitted key words that pertained to radio frequency, airspeed, or approach/ departure instructions. Pilots only partially read back instructions involving heading, radio frequency, and airspeed aviation topics and grouped numbers in a radio frequency, airspeed, or heading. Pilots and controllers communications became more conversational and verbose when their transmissions included advisory or request speech acts. Omitting and grouping numbers in transmissions may be strategies used to minimize time on frequency. Ironically, these strategies may create the problems that pilots and controllers are trying to prevent.

FY. "Radar Separation Standards Working Group Volume Two," Civil Aviation Authority, CS Report 9237, January 1993.

1. Topic: Empirical or semi-empirical expressions

FZ. Ramsey, J.L., "Effectiveness Limitations of Midair Collision Avoidance Strategies," Paper presented at the 29th Annual meeting, Institute of Navigation, 1973, *Navigation,* vol. 20, no. 4, p. 357-369.

1. Provides data to help resolve which classes of techniques ought to be used to prevent midair collisions, based on a statistical analysis of recent midair collisions.

GA. Ranger, F.W., "Test and Evaluation of the Conflict Alert Function (High Altitude) with the NAS En Route A3d2, 1 System," FAA Report RD75-117, 1975, AD-A014 103, N76-13037

1. Reports on tests conducted at NAFEC in a beacon-only high-altitude

environment with simulated digital target data. The tests were designed to evaluate the performance of the conflict alert function.

GB. Ratcliff, S. and R. L. Ford, "Conflicts between Random Flights in a Given Area," *Journal of Institute of Navigation,* Vol. 35, No. 1, 1982

GC. Ratcliffe, S., "Collision Avoidance and the Future of Air Traffic Control," Paper presented at the International Conference, Hanover, Germany, *Journal of Navigation,* vol. 26, n 4, pp. 423-230, 1973

   1. Answers questions about the optimum division of responsibility between the aircrew and ground ATC, and about the fundamental principles of traffic flow organization.

GD. Ratliffe, S, "Air Traffic Control and Mid-Air Collisions," *Electronics and Communications Engineering Journal,* v.2 no. 5. (10/1/90).

GE. Reich, Peter G., "A Theory of Safe Separation Standards for Air Traffic Control," Farnborough, United Kingdom: Royal Aircraft Establishment, RAE Technical Reports Nos. 64041, 64042, 64043, 1964

   1. Topic: Mathematical models for collision risk

   2. We understand that the three parts of this entry are identical to the three parts of the following entry.

GF. Reich, Peter G., "Analysis of Long-Range Air Traffic Systems: Separation Standards--I, II, and III," *The Journal of (the Institute of) Navigation,* Vol.19 (1966), No. 1, pp. 88-96; No. 2, pp.169-176; No. 3, pp. 331-338.

   1. Topic: Mathematical models for collision risk

   2. We understand that the three parts of this entry are identical to the three parts of the preceding entry.

GG. Reich, Peter G., "An Analysis of Planned Aircraft Proximity and Its Relation to Collision Risk, with Special Reference to the North Atlantic Region 1965-71," Farnborough Hants, United Kingdom: Royal Aircraft Establishment, Ministry of Aviation, RAE Technical Reports No. 64042, 1964.

1. Note that this paper has the same report number as the second report in the preceding entry.

GH. Richie, Joseph M., "Description of the Derivation of the Collision Risk Model Used in the Vertical Separation Simulation Risk Model," (Technical Note) Atlantic City Airport: FAA Technical Center, Report No. DOT/FAA/CT-TN88/38, February 1989, 20 pgs. (ADNUMBER: ADA205109).

1. This report presents a brief description of the derivation of the collision risk equations for the use on the vertical separation Midair Collision Simulation Risk Model. It also describes the estimation of the Collision Risk Model parameters for the current 2000-foot standard and the proposed 1000-foot planned vertical separation standard. The model itself consist of specialized computer programs and systematic procedures that realistically and economically simulate aircraft flight-planned movements in the National Airspace System (NAS) . These aircraft movements are based on flight plans and tracking data transmitted to Central Flow Control Facility (CFCF) from all the 20 centers that make up the NAS. The task is to find the frequency, Na, with which a pair of aircraft flying at and above flight level (FL)290 would, by flight-planned intent, be proximate (near each other) in the NAS. The purpose of this mathematical model is to make a quantitative judgment about the safety of the proposed 1000-foot vertical separation, and provide an estimate of the risk of midair collision due to the loss of 1000-foot planned vertical separation. As the result of this first phase of the study, it is recommended that the model be enhanced to do the following: 1) step climbing, and 2) point-to-point navigation. Keywords: Tracking system; Proximity shell; Separation vectors; Collision slab; Central flow.

GI. Rigolizzo, R., "Preliminary Estimate of System Performance Requirements Necessary to Support a 1,000-Foot Vertical Separation Standard At and Above Flight Level 290," Atlantic City Airport, NJ: Federal Aviation Administration Technical Center, DOT/FAA/CT-TN83/41, February 1984.

GJ. Rigolizzo, Robert, "A Preliminary Procedure for Estimating Component Error Histograms Associated with Aircraft Vertical System Performance Over CONUS--First Draft," Atlantic City Airport, NJ: Federal Aviation Administration Technical Center, ACT 220, RTCA Paper No. 38-83/SC150-27, January 1983

GK. Rigolizzo, Robert, "Reduction and Analysis of Mode C Altitude Data Collected at High Altitudes Over the Continental United States," Atlantic City, NJ: FAA Technical Center, Report Nos. DOT/FAA/EM-82/9A, DOT/FAA/CT-81/53A, March 1982

GL. "Risk Analysis Report: Airspaces Australia Airspace Risk Model," August 1995.

   1. Topic:General Risk Estimation Methodologies

GM. Rockman, Mark J, "A Preliminary Mathematical Model for the Radar Separation Minimum," McLean, VA: MITRE CAASD, Report No. MP 95W0000095, May 1995

   1. Appendix B is "Origin of the Radar Separation Minima," which was drawn on heavily for the "History" section of this report.

GN. Rockman, Mark J., "A Review of the Current Radar Separation Minima and Some Thoughts on Reducing Them," McLean, VA: MITRE CAASD, Report No. WN 940000099, 29 July 1994

GO. Rodin, E.Y, S,M Amin, and C. Ruan, "Collision Avoidance and Low-Observable Navigation in a Dynamic Environment." *Mathematical and Computer Modeling,* v. 16. no. 5 (1992).

GP. Roelen, A., et. al., "Systematic Safety Study on the Feasibility of a Structured Approach Using a Quantified Causal Tree," Nationaal Lucht - En Ruimtevaartlaboratorium (National Aerospace Laboratory), NLR, The Netherlands, NLR CR 96206 L, 3/15/96.

   1. Topic: Safety assessment methods + a little human factors

GQ. Rome, H. James, "Development the Unified Risk Model for Evaluation of Current and Future Airspace," Lowell, MA: University of Massachusetts

   1. James Rome, Associate Professor. Department of Electrical Engineering Phone: 508 934 3309 Fax: (508) 934 3027. email: romej@woods.uml.edu. EDUCATION.... http://www.uml.edu/Dept/EE/Faculty/JamesRome.html

   2. I am familiar with Dr. Rome's work for the FAA. It is principally directed toward the oceanic (procedural) environment and projects the benefits of GPS and Automatic Dependent Surveillance. He makes extravagant claims for those benefits and does not consider

all the air traffic environment. The model is mostly
probabilistic but depends upon untested assumptions about
operations.

  a. Collision Risk Modeling and aircraft separation analysis for
     the FAA.

  b. Unified Risk Model

GR. RTCA (Radio Technical Commission for Aeronautics), "Initial Report on
    Minimum System Performance Standards for Vertical Separation Above
    Standard AT and Above Flight Level 290," RTCA Paper No.
    561-84/SC150-72, November 30, 1984. [RTCA, One McPherson Square, 1425
    K Street, N.W., Suite 500, Washington, D.C. 20005.]

GS. RTCA, "Action Plan - Free Flight: Dynamic Air Traffic Management,"
    Washington: RTCA, August 15, 1996

GT. RTCA, "Final Report of RTCA Task Force 3, Free Flight
    Implementation," Washington: Radio Technical Commission for
    Aeronautics, Reprinted February 1996

GU. RTCA, "Minimum Aviation System Performance Standards: Required
    Navigation Performance for Area Navigation," Washington: RTCA
    (SC-181), doc. no. DO-236, Jan. 27, 1997

  1. Includes requirements intended to meet ICAO RGCSP [Review of the
     General Concepts of Separation Panel] definition of Required
     Navigation Performance [RNP]. This document only addresses the
     lateral aspects of RNP. Vertical and longitudinal requirements,
     including time, will be addressed in the future.

GV. RTCA, "Report of the RTCA Board of Directors' Select Committee on
    Free Flight," Washington: RTCA, January 18, 1995. [Available through
    RTCA, Incorporated, 1140 Connecticut Avenue, N.W., Suite 1020,
    Washington, D.C. 20036, (202) 833-9339.]

GW. RTCA, "Terms of Reference, Air Traffic Services Safety and
    Interoperability Requirements," RTCA SC-189/EUROCAE WG 53.

GX. Rudisill, Marianne, "Line Pilots' Attitudes About and Experience With
    Flight Deck Automation: Results of an International Survey and
    Proposed Guidelines," *Proceedings of the Eighth International
    Symposium on Aviation Psychology, Columbus, OH, April 1995*, pp. 6,
    (458KB). [See Langley Technical Report Server.]

1. Abstract: A survey of line pilots' attitudes about flight deck automation was conducted by the Royal Air Force Institute of Aviation Medicine (RAF IAM, Farnborough, UK) under the sponsorship of the United Kingdom's Civil Aviation Authority and in cooperation with IATA (the International Air Transport Association). Survey freehand comments given by pilots operating 13 types of commercial transports across five manufacturers (Airbus, Boeing, British Aerospace, Lockheed, and McDonnell-Douglas) and 57 air carriers/organizations were analyzed by NASA. These data provide a "lessons learned" knowledge base which may be used for the definition of guidelines for flight deck automation and its associated crew interface within the High Speed Research Program. The aircraft chosen for analysis represented a progression of levels of automation sophistication and complexity, from "Basic" types (e.g., B727, DC9), through "Transition" types (e.g., A300, Concorde), to two levels of glass cockpits (e.g., Glass 1: e.g., A310; Glass 2: e.g., B747-400). This paper reports the results of analyses of comments from pilots flying commercial transport types having the highest level of automation sophistication (B757/B767, B747-400, and A320). Comments were decomposed into five categories relating to: (1) general observations with regard to flight deck automation; comments concerning the (2) design and (3) crew understanding of automation and the crew interface; (4) crew operations with automation; and (5) personal factors affecting crew/automation interaction. The goal of these analyses is to contribute to the definition of guidelines which may be used during design of future aircraft flight decks.

GY. Runnels, Mark H., et. al., "Concepts for Future NAS Operations," McLean, VA: MITRE CAASD, Report No. MTR 950000107V2, September 1995

GZ. Sadoune, Michael, "A Model of Aircraft Interaction for Separation Standards," 1988.

HA. "Safety Assessment Methods and Tools to Support Safety Management of Transport Airplanes In Commercial Service," DRAFT [source unknown]

HB. Sammonds, R.I., and G.W. Stinnett, Jr., "Hazard Criteria for Wake Vortex Encounters," NASA TM X-62473, August 1975.

HC. Schmidt, David K., "On Modeling ATC Workload and Sector Capacity," *J Aircraft,* Vol. 13, No, 7, July 1976

1. Topic: Mathematical models for collision risk

HD. Schmidt, David K., "On the Conflict Frequency at Air Route
Intersections," *Transportation Research,*vol. 11, pp. 351-355, 1977,
Great Britain: Pergamon Press.

1. Topic: Mathematical models for collision risk

HE. Schwartz, Jonathan L., "Conflict-Free Speed Maneuvers for ATC
Maneuver Planning," McLean, VA: MITRE, Report No. MTR-91W00097

HF. Schwartz, Jonathan L., "Conflict-Free Vectoring for ATC Maneuver
Planning," McLean, VA: MITRE, Report No. MTR-91W00092, January 1992

HG. Schwartz, Jonathan L., "Relative Space Protection Regions for
Aircraft Conflict Analyses," McLean, VA: MITRE, May 1991, Report No.
MTR-91W00041

HH. Shank, E. M. and K. M. Hollister, "Precision Runway Monitor,"
Lincoln Laboratory Journal, Vol. 7, No. 2 (1994), Lexington, MA:
Massachusetts Institute of Technology Lincoln Laboratory.

HI. Shank, E. M. and K. M. Hollister, K. M., "A Statistical Risk
Assessment Model for the Precision Runway Monitor System," Lexington,
MA: Massachusetts Institute of Technology Lincoln Laboratory, 1992.

HJ. Shank, Eric M. and Katherine M. Hollister, "A Statistical Risk
Assessment Model for the Precision Runway Monitor System," *37th
Annual Air Traffic Control Association Conference Proceedings, Fall
1992,* November 1-5, 1992, Atlantic City, New Jersey.

HK. Sharpe, A. G.," Application of the 5NM Radar Separation Standard at
Ranges up to 160NM from Claxby, Debden and Pease Pottage SSRs," Civil
Aviation Authority, CAA Paper 91013, June 1991.

1. Topic: Empirical or semi-empirical expressions

HL. Shen, M. M., G. Hunter, and J. Sorensen, "Analysis of Final Approach
Spacing Requirements Part II," FAA Terminal Air Traffic Control
Automation Program, Lexington, MA: Massachusetts Institute of
Technology Lincoln Laboratory, 1992.

HM. Shepherd, Roger, Rick Cassell and Edwin Alphonso, "Reduced Aircraft
Separation on Final Approach - A Review of Separation Risk
Models--Draft report," Alexandria, VA: Rannoch Corporation, June 5,

1996

HN. Shuch, H. Paul, "A New Approach to Collision Avoidance," *Sport Aviation* 36(6):26-28, June 1987.

HO. Shuch, H. Paul, "General Aviation Collision Avoidance Alternatives," *Journal of Transportation Engineering,* 115(5):474-492, September 1989.

HP. Shuch, H. Paul, "Near Midair Collisions as an Indicator of General Aviation Collision Risk." Berkeley, CA: University of California, Institute of Transportation Studies, Series UCB-ITS-DS-90-2, 214 pp, March 1990, $50.

    1. In a separate search of journal material, H. Paul Shuch showed up affiliated with a central Pennsylvania college, so he is still doing work in this general area.

HQ. Shuch, H. Paul, "Near Midair Collisions: How Many Really Occur?" *Risk Analysis* (in press).

HR. Shuch, H. Paul, "The Influence of Flight Experience on Midair Collision Risk Perception," *Accident Analysis and Prevention*, 24(6):655-660, October 1992.

HS. Siddiquee. W., "A Mathematical Model for Predicting the Number of Potential Conflict Situations at Intersecting Air Routes," *Transportation Science,* 7, May 1973, pp. 158-167.

    1. Topic: Mathematical models for collision risk

HT. Simpson, Robert W., and Raymond A. Austrotas, "Modelling Risk in ATC Operations with Ground Interventions," MIT Flight Transportation Laboratory Report R 91-6, July 1991.

HU. Simpson, Robert W. and Amedeo R. Odoni, "Modeling of Air Traffic Encounters: Estimating Collision Risk, Near Miss and Conflict Rates in ATC Operations," Cambridge: MIT Flight Transportation Laboratory, July 1988, FTL Report R-88-4.

HV. Simpson, Robert W., "Chapter 3: Encounter Models - Uncontrolled Flow of Air Traffic," (draft of 12/28/90) in *Air Traffic Control Engineering* (draft manuscript), Cambridge: (formerly MIT, now Flight Transportation Associates)

1. This is a rather mathematical treatment of the kinematics of an encounter, some probability theory, and the application of both to encounter models.

HW. Sinah, Agam N., Monica S. Alcabin, and John E. Lebron, "Perspective on the Role of System Level Modeling and Simulation in Achieving the Future NAS Vision," McLean, VA: MITRE/CAASD http://www.caasd.org/html_files/MP93W49/MP93W49.html

HX. Slater, K. and F. Cusden, "A Preliminary Assessment of a Methodology for Assessing NERC Surveillance System Separation Minima," CS Report 9420, Civil Aviation Authority, London, April 1994.

HY. Slater, K., "An Analysis of Bias Errors for the Proposed Composite Radar Boundary in the TC Welin and Cowley Sectors," Civil Aviation Authority, London, 1995. R&D Report 9602, Civil Aviation Authority, London, January 1996.

1. Topic: Empirical or semi-empirical expressions

HZ. Smith, E.J., "Hazard Analysis of Route Separation Standards for EUROCONTROL," *DNV Technica,* 1994.

IA. Smith, E. J., "Hazard Analysis of Route Separation Standards for European Organization for the Safety of Air Navigation," EUROCONTROL, C4508-1, *DNV Technica,* February 1996

1. Topic:General Risk Estimation Methodologies

IB. Software safety: (no formal title) - Formal methods and software safety comp.software-eng archive file "safety" last; changed 31 Jul 1993 This file contains information on the following...; --http://dxsting.cern.ch/sting/comp.software-eng/safety.txt

1. This internet file is mainly a discussion of software safety and formal methods for ensuring same.

IC. Sorensen, J. A., M. M. Shen, and G. C. Hunter, "Analysis of Final Approach Spacing Requirements, Part I," San Jose, CA: Seagull Technology, Inc., Report 91112-01, 1991.

ID. Sorensen, J.A., et. al., "Horizontal Collision Avoidance Systems Study," Systems Control, Inc., FAA Report RD 73-203 (TSC-73-36), 1973, AD/A-004 536

  1. Results of an analytical study of the merits and requirements of collision avoidance systems which operate chiefly by commanding horizontal maneuvers.

IE. Steingr¡mur, P ll K rason, "A Model for the Estimation of Airplane Collision Risk" (Thesis), Reykjav¡k,Iceland: University of Iceland, 1991 ?

IF. Stengel, R. (1995). "Suggested Revisions to the Aircraft Wake Vortex Separation Standards," Princeton, NJ: Princeton University, 1995. [Presented at the FAA/Industry Wake Vortex Program Review. January 17-18, 1996, Cambridge, MA.]

IG. Stepner, D.E., "Modeling of Aircraft position Errors with independent Surveillance," AIAA Paper 73-162, 1973

  1. In order to reduce present air traffic standards, a quantitative measure of the safety level of a particular air route structure must be established. The most important factor in determining route safety is the distribution of aircraft position errors about their intended tracks.

IH. Stewart, E. C., "A Study of the Interaction between A Wake Vortex and an Encountering Airplane," AIAA Paper No. 93-3642, August 1993.

II. Swedish, W. J., "Evaluation of the Potential for Reduced Longitudinal Spacing on Final Approach," McLean, VA: The MITRE Corporation, Report No. MTR-79W00280, 1979. Prepared for US DOT/FAA/Report No. FAA-EM-79-7.

IJ. "Systems Safety Description of a Flight Operation," [author unknown], circa 1973

IK. Technologie France Number 11 (English version). Summary: Interview. Marianne Grunberg Manago, President of the Academy of Science Prospects. A strategic research guidance.. http://www.adit.fr/Produits/TF/Anciens/TF11a.html

IL. "The Tolerability of Risk from Nuclear Power Stations," *Health and Safety Executive,* Revised Edition, London: HMSO:1992.

  1. Topic: Risk Tolerability

IM. Thomas, Ralph E. and Loren J. Rosenthal, "Probability Distributions of Altitude Deviations," Moffett Field, CA: NASA Ames Research

Center, NASA Contractor Report No. 166339, June 1982

IN. Thompson, S.D., "Terminal Area Separation Standards: Historical Development, Current Standards, and Processes for Change," Lexington, MA: MIT Lincoln Laboratory, Report No. ATC-258, 16 January 1997

IO. Vicroy, D., R. Bowles, J. Brandon, G. Greene, F. Jordan, Jr., R. Rivers, E. Stewart, H.P. Stough III, R. Steuver, "NASA Wake Vortex Research," (NASA Langley Research Center), Anaheim, CA: 19th Congress of the International Council of the Aeronautical Sciences, September 19-23, 1994.

IP. Westcott, Mark and David Gates, "Distance-Based Collision Risk Modelling (with D. Gates)," Report for the Civil Aviation Authority, Report DMS-C 92/48, 31 August 1992;

   1. Dr Mark Westcott
   CSIRO Mathematical and Information Sciences
   GPO Box 664, Canberra ACT 2601
   Location: Information Sciences Building (108), North Road
   Australian National University Campus
   tel: + 61 6 216 7253
   fax: + 61 6 216 7255
   e-mail: mark.westcott@cmis.csiro.au
   http://www.cbr.dms.csiro.au/~markw/reports.htm

   2. A novel, approach to collision risk estimation in oceanic airspace, bounding actual navigation errors with values based on perceived navigation errors.

IQ. Wolf, Ian G., *Beacon Radar Separation Minima for Jacksonville ARTCC Utilizing Digitized Radar,* Washington: Federal Aviation Administration, Unpublished